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ANALYSIS OF WATER BARRIER LINE CHARGE PLUME MEASUREMENTS

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The Naval Surface Warfare Center, Dahlgren Division (NSWCDD) is developing technology for a concept that has the potential to be very effective in defending Navy platforms against high-speed, sea-skimming antiship cruise missiles (ASCMs). This concept uses a new kill mechanism, a wall of water, to provide a low-cost, universal terminal defense system for Navy ships. This wall of water, or water barrier, is formed from the shallow detonation of multiple underwater explosive charges. This water barrier will protect the ship from the attacking sea skimmers. To support the development and evaluation of the Water Barrier Concept, underwater detonation tests were conducted in July 1995 to generate a water barrier from the single-point detonation of simulated continuous and discrete line charges. The simulated line charges were fabricated from scaled charges of Composition C-4 demolition blocks. Electrical conductivity and microwave absorption measurements were made on the barrier plume cross section to determine the density or quantity of water ejected in the air from the single-point detonation of the scaled line charges. This report presents the results from the microwave absorption and electrical conductivity measurements of the scaled barrier at cross-section heights of 11.5 and 25 ft, respectively.

14. SUBJECT TERMS

Antiship cruise missile (ASCM), Shallow Water Mine Clearance Technology, continuous line charge, discrete line charge, terminal ship defense, point defense, ship self defense, AAW ship defense, water barrier, water plumes, water density measurements, microwave absorption density measurements, conductivity water density measurements, hydrodynamic model of water plumes

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FOREWORD

Under the sponsorship of Mr. Dave Siegel, Code 351, Office of Naval Research (ONR), the Naval Surface Warfare Center, Dahlgren Division (NSWCDD) is developing technology that uses a new kill mechanism, a wall of water, to provide a low-cost, effective terminal defense of Navy ships against high-speed, sea-skimming antiship cruise missiles (ASCMs). The Water Barrier Ship Self Defense generates a wall of water from the shallow detonation of multiple underwater explosive charges. This wall of water, or water barrier, will protect the ship from sea-skimming ASCMs. This wall of water will prevent target debris and warhead fragments produced at very short range from causing severe damage to own ship. Furthermore, the barrier will defeat the fuzing and structure of ASCM sea skimmers that have penetrated the self-defense layer.

To evaluate a water barrier generated from the single point detonation of simulated continuous and discrete line charges, thirteen underwater detonation tests were fired during July 1995 in a water-filled quarry in Rustburg, Virginia. The quarry is operated by Dynamic Testing, Incorporated (DTI), a subsidiary of NKF Engineering, Incorporated. This report presents the results from the electrical conductivity and microwave absorption measurements at barrier-plume cross-section heights of 11.5 and 25 ft, respectively, of the scaled barrier plume produced by the underwater detonation of continuous and discrete line charges in this series of test shots.

The Naval Surface Warfare Center test team included representatives of two Divisions. Planning and arrangement of the field test were carried out by L. Lipton of Code 450 and J. Connor of Code 9540, Naval Surface Warfare Center, Indian Head Division (NSWCIHD). Microwave absorption measurement equipment was provided and operated by K. Boulais, J. Choe, and K. Irwin from Code B44 of NSWCDD. The electrical conductivity probe equipment was provided and operated by L. Lipton of NSWCIHD. Video equipment was set up and operated by J. Connor of NSWCIHD, assisted by C. Higdon of NSWCDD.

Approved by:

J. W. WALTERS, Deputy Head (Acting)
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GLOSSARY

ASCM	Antiship cruise missile
C-4	M113 demolition block of Composition C-4
D	Maximum bubble diameter of line charge
DET	Distributed explosive technology
DLVA	Direct logarithmic video amplifier
DTI	Dynamic Testing, Incorporated
EN-ATD	Explosive Neutralization-Advanced Technology Demonstration
EWL	Equivalent water length
EWL TOTAL TIME	Total time that EWL is equal to or above a specific value
HTL	Hi Test Laboratories
IDEAL DEPTH	Ideal detonation depth of line charge
L	Length of line charge
M58	Linear demolition charge
NSWCDD	Naval Surface Warfare Center, Dahlgren Division
NSWCIHD	Naval Surface Warfare Center, Indian Head Division
PREDICTED DEPTH	Predicted detonation depth of line charge
ONR	Office of Naval Research
SABRE	Shallow water assault breeching system
TWTA	Traveling wave tube amplifier
SZ	Surface zero

INTRODUCTION

BACKGROUND

Under the sponsorship of the Office of Naval Research (ONR), the Naval Surface Warfare Center, Dahlgren Division (NSWCDD) is developing technology for a concept that has the potential to be very effective in defending Navy platforms against high-speed, sea-skimming, antiship cruise missiles (ASCMs). This concept uses a new kill mechanism, a wall of water, to provide a low-cost, universal terminal defense system for Navy ships. This wall of water, or water barrier, is formed from the shallow detonation of multiple underwater explosive charges. This concept can be employed to slow or stop target debris and warhead fragments from missiles killed at very short range to preclude significant damage to own ship. Furthermore, the water barrier would defeat the fuzing and structure of ASCM sea skimmers that have penetrated the self-defense layer. Close-in employment of the water barrier concept would increase the engagement space of self-defense weapons and help reduce detection range requirements.[1-3]

Deployment of the Water Barrier Defense can build on the Shallow Water Mine Clearance Technology that deploys line charges.[4-5] Line charge deployment solves the problem of barrier plume formation because the barrier requires the near simultaneous detonation of underwater explosive charges at a specified depth and spacing to maximize the amount of water ejected into the air to defeat sea skimmers. To support the development and evaluation of a water barrier that uses line charges, underwater detonation tests of scaled line charges were conducted during July 1995 in a 130-ft-deep, water-filled quarry operated by Dynamic Testing, Incorporated (DTI) in Rustburg, Virginia. The purpose of these tests was to evaluate a water barrier generated from the single-point detonation of simulated continuous and discrete line charges and to determine the amount and density of water ejected into the air by the subsurface detonation of these line charges. The water barrier plumes were generated by the single-point underwater detonation of Composition C-4 M113 demolition blocks that were configured into continuous line charges of 30 to 56 ft in length. Barrier plumes were also produced from the single-point underwater detonation of discrete line charges that consisted of five to eight 10-lb charges separated by 8 ft and fabricated from C-4 M113 demolition blocks. Line charge depths and horizontal separation of the discrete charges were chosen to maximize the amount of water ejected into the air.[6-7]

Two measurement techniques, using microwave absorption and electrical conductivity, were employed to determine the amount and density of water in the barrier plume cross section. A microwave antenna transmitting a 4-GHz signal and a receiving antenna are placed perpendicular to the charge line at a height of 25 ft above the water surface. Fifteen conductivity probes, spaced 1 ft apart, are placed on a steel cable 11.5 ft above the water surface and in the same vertical plane as the microwave beam. The cable and probes are perpendicular to the charge line with the probes centered about the charge line.[8-10] The plumes were photographed with 30-picture-per-second super VHS video cameras placed parallel and normal to the charge line. Dimensions of the barrier plume produced by the test shots were determined from digitized images captured from the video tapes.[11] The microwave absorption and electrical conductivity measurements will be used in conjunction with the video data on the same barrier plumes to evaluate the water barriers generated from the single point detonation of scaled simulated line charges and to verify a hydrodynamic computer model of plume generation from the shallow detonation of multiple underwater explosive charges.[7] This report presents the results from the electrical conductivity and microwave absorption measurements at cross section heights of 11.5 and 25 ft, respectively, of the scaled barrier plume produced by the underwater detonation of continuous and discrete line charges in this series of test shots.

EVOLUTION OF AN UNDERWATER EXPLOSION

An explosion is a chemical reaction in a substance that converts the original material into a gas at very high temperature and pressure. A reaction front—the detonation wave—propagates through the material at a velocity of several thousand meters per second. The detonation wave from an underwater explosion of a single charge is transmitted into the surrounding water as a propagating shock front that travels radially outward toward the air/water interface above the detonation point. The wave reflects into the water as a rarefaction in order to conserve momentum and energy at the surface. Since water cannot sustain tension, a whitened area of cavitation is formed that rises from the surface. A shock is also propagated into the air, but is far from the region above the explosion long before a water plume is formed.

The gas bubble, containing the gaseous explosion by-products, expands rapidly outward at a high velocity to relieve its high internal pressure. As the bubble rapidly expands, the bubble assumes a nearly spherical shape regardless of the initial charge shape. The water above the charge erupts upward—driven first by the reflected shock and later by the mass motion of the water pushed by the expanding bubble. Surface and plume phenomena produced by detonation of a spherical, single charge are discussed in the classic underwater explosion treatise by Cole[12] and in the reports by Young.[13-14] For relatively shallow detonations of long linear line charges, such as fired for this test program, evolution from undisturbed surface to fully developed, vertical plumes is complete in a few (~ 2) seconds. Somewhat more than two (2) additional seconds are required for the water to subside to the surface.

Spray Dome

The first visible event at the surface above the explosion is the cavitation whitening of the water due to the reflected rarefaction. The cavitated layer is ejected vertically upward with a speed that satisfies mass and momentum conservation laws. The reflection process produces a dome of water droplets whose profile on the photographic and video tape images suggests the Gaussian bell curve as viewed down the charge line.

Bubble Phenomena

For the scaled firing depths used for these tests, the cylindrical explosion gas bubble arrives at the surface before the shock reflection process has run its course. The bubble rises inside the cavitated Gaussian-like dome creating a hollow core that is isolated from the atmosphere. This core increases in volume until its internal pressure is somewhat less than ambient. At the firing depths chosen for these tests, a rapidly rising jet is often seen rising above the top of the dome as the gases vent upward to the atmosphere. As internal pressure decreases, horizontal and vertical growth of the plume slows. The bubble collapses and its bottom surface rushes up into the hollow core and pushes through the walls of the plume. Radial plumes are generated that are visible on camera records.

Shockwave Interaction

When multiple discrete charges are detonated nearly simultaneously close to one another at about the same depth, each charge produces a nearly spherical shockwave. The shocks interact with one another at the water/air interface approximately midway between the charge support floats. A large impulse is delivered to the surface water between the charges; the water at these locations acquires large velocities exceeding those imparted to the cavitated water in the dome. Viewed from the side, a vertical spike appears, which moves ahead of the dome to significantly greater heights than the dome from detonation of a single charge. The horizontal component of velocity imparted to the surface water by the shock interaction pushes water ahead of the shock-produced dome. The consequent plume generated from the shallow detonation of multiple charges is wider than that produced by detonation of a single charge. This surface interaction results in a pancake of water added to the dome development. The plane of the pancake is normal to the axis of the line charge. Continuous charges produce domes without spikes induced by shock interactions.

Line Charge Plume Formation

Figure 1 shows the frontal view of a continuous line charge plume at various stages of development in one-tenth of a second time increments just after a shallow detonation. Vertical and horizontal scales in ft are provided to give a sense of physical dimension. This plume is generated from a continuous line charge that is 56 ft in length. The continuous line charge consists of 56 Composition C-4 M113 demolition blocks with a charge density of 1.25 lb/ft and detonated at a depth of approximately 8 ft. The single detonation point is on the right end of the line charge. A rapidly rising dense vertical jet is seen rising above the top of the spray dome to eventually reach a height of 70 to 80 ft in one second. As the bubble collapses and its bottom surface rushes up into the hollow core and pushes through the walls of the central plume, secondary plumes are formed in front and back of the still-present jet. Since the line charge is continuous, the shock interactions are almost negligible.

Figure 2 shows the profile or side view of the continuous line charge plume as seen down the charge line from the right-hand side or detonation end. After detonation, the cavitated

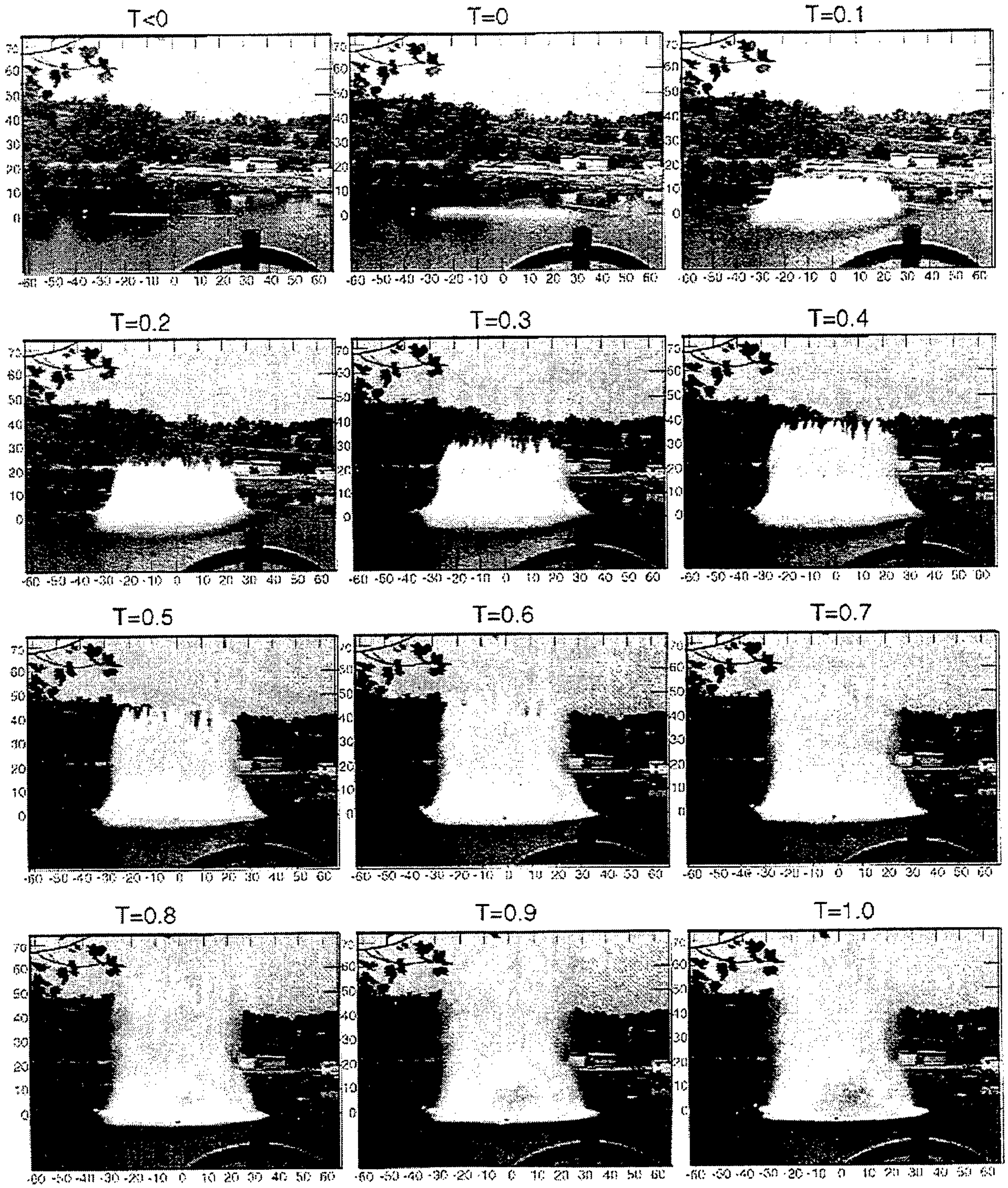


FIGURE 1. CONTINUOUS LINE CHARGE, FRONT VIEW

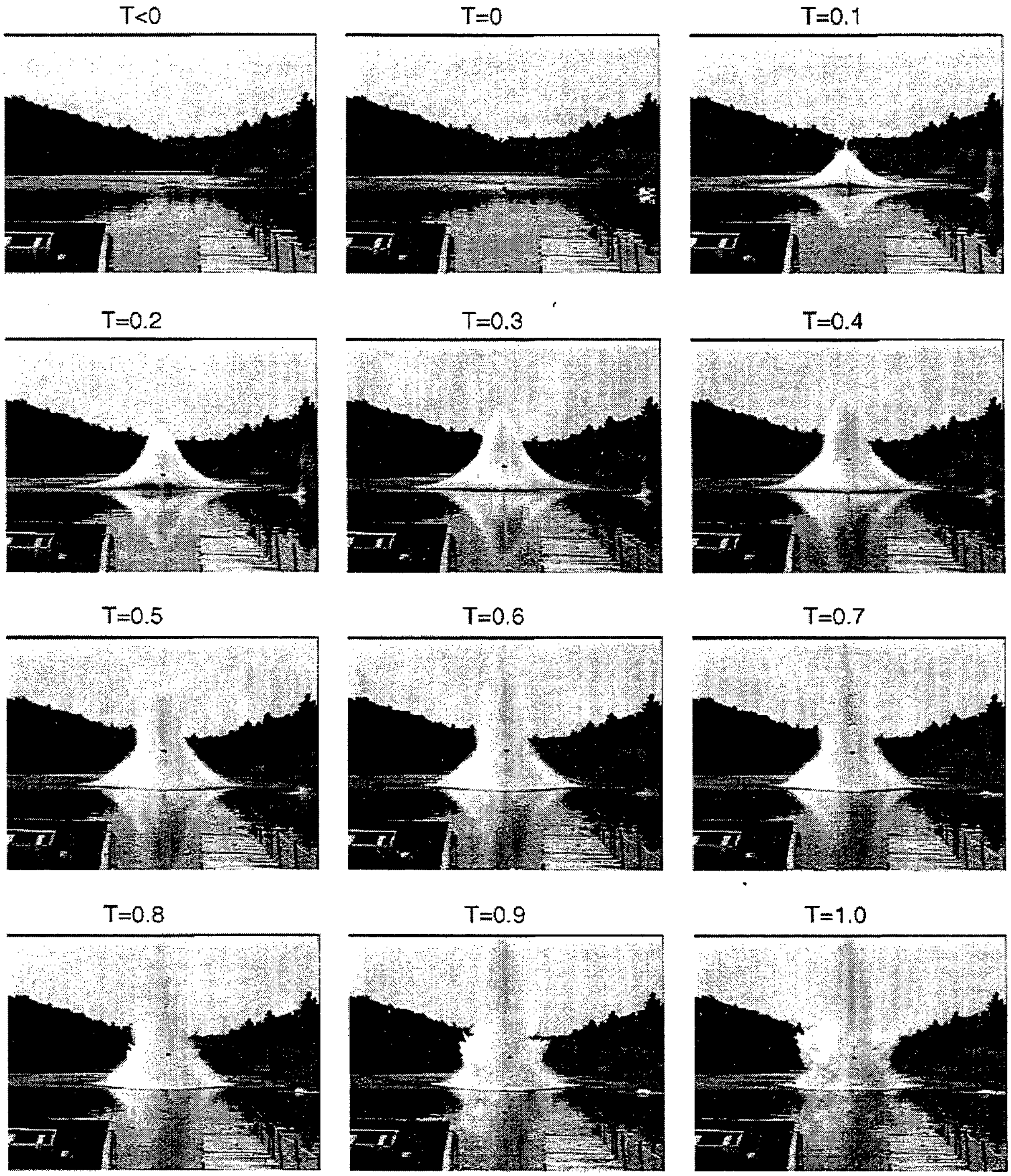


FIGURE 2. CONTINUOUS LINE CHARGE, SIDE VIEW

Gaussian-like spray dome rises into the air. A rapidly rising jet is seen rising above the top of the spray dome as the explosive gases push upward to the atmosphere. As internal pressure decreases, horizontal and vertical growth of the central jet slows. The secondary plumes, formed by the rising bubble, emerge at about 0.8 sec as they are ejected upward and outward from the spray dome and jet.

Figure 3 shows the frontal view of a discrete line charge plume that is generated from eight, 10-lb charges of C-4 spaced about 8 ft apart and detonated at a depth of approximately 8 ft. Each discrete charge is fabricated from eight M113 demolition blocks. The resultant line charge length is 56 ft. The single detonation point is to the right of the discrete line charge. As observed in earlier field tests of the simultaneous detonation of discrete charges, the interaction of the shock intersections with the free surface is clearly visible.[15] The seven shockwave interactions between the adjacent discrete charges are seen to move rapidly ahead of the rising jet and spray dome. The shock interaction heights are well above 60 ft at one second after detonation. As the bubble collapses, secondary plumes rapidly emerge in front and back of the still-present central jet. Figure 4 shows the profile of the discrete line charge plume as seen down the charge line from the right-hand side or detonation end. Clearly, both line charge types successfully form a wall of water from the scaled C-4 charges along with the emergence of the secondary plumes.

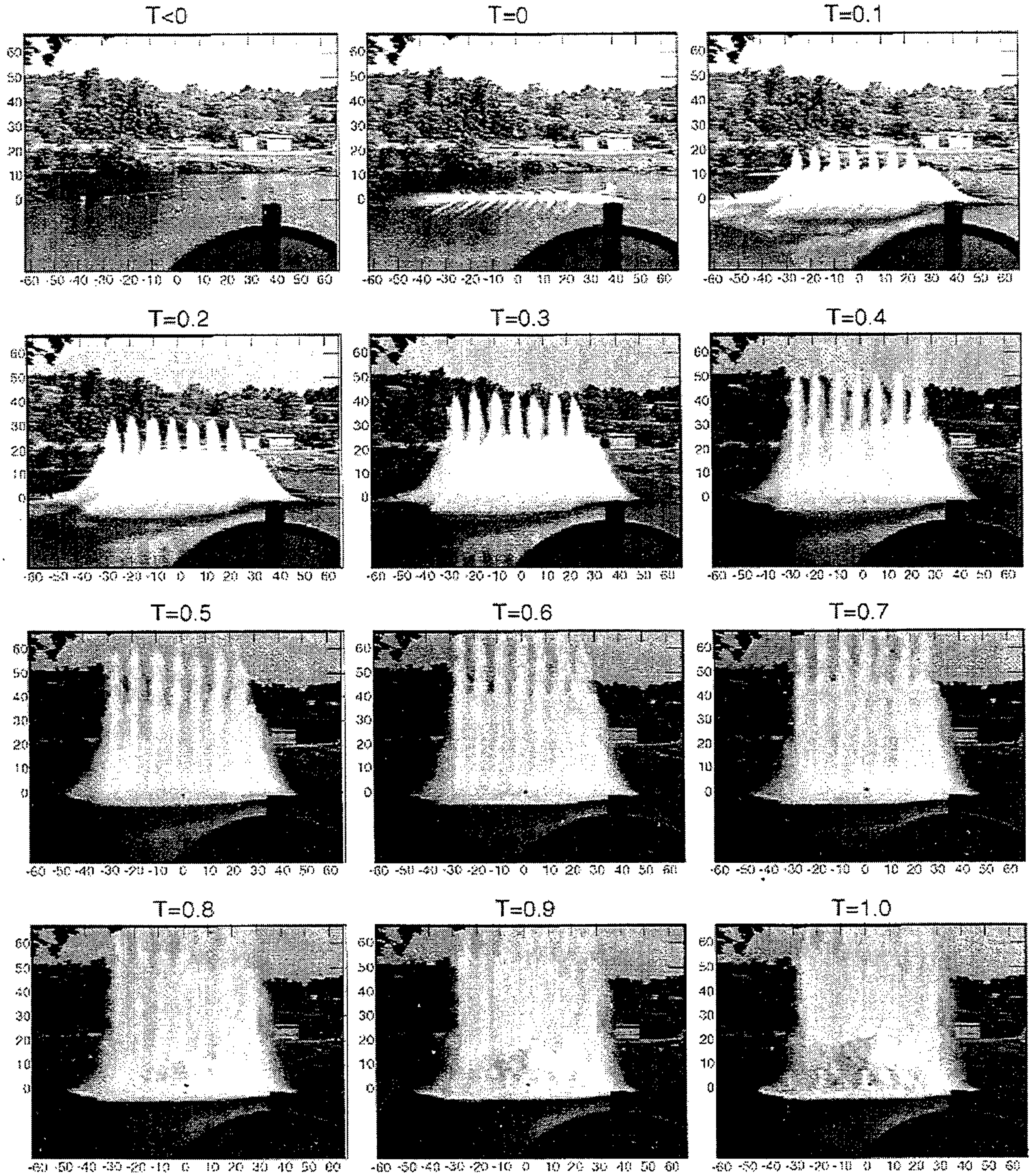


FIGURE 3. DISCRETE LINE CHARGE, FRONT VIEW

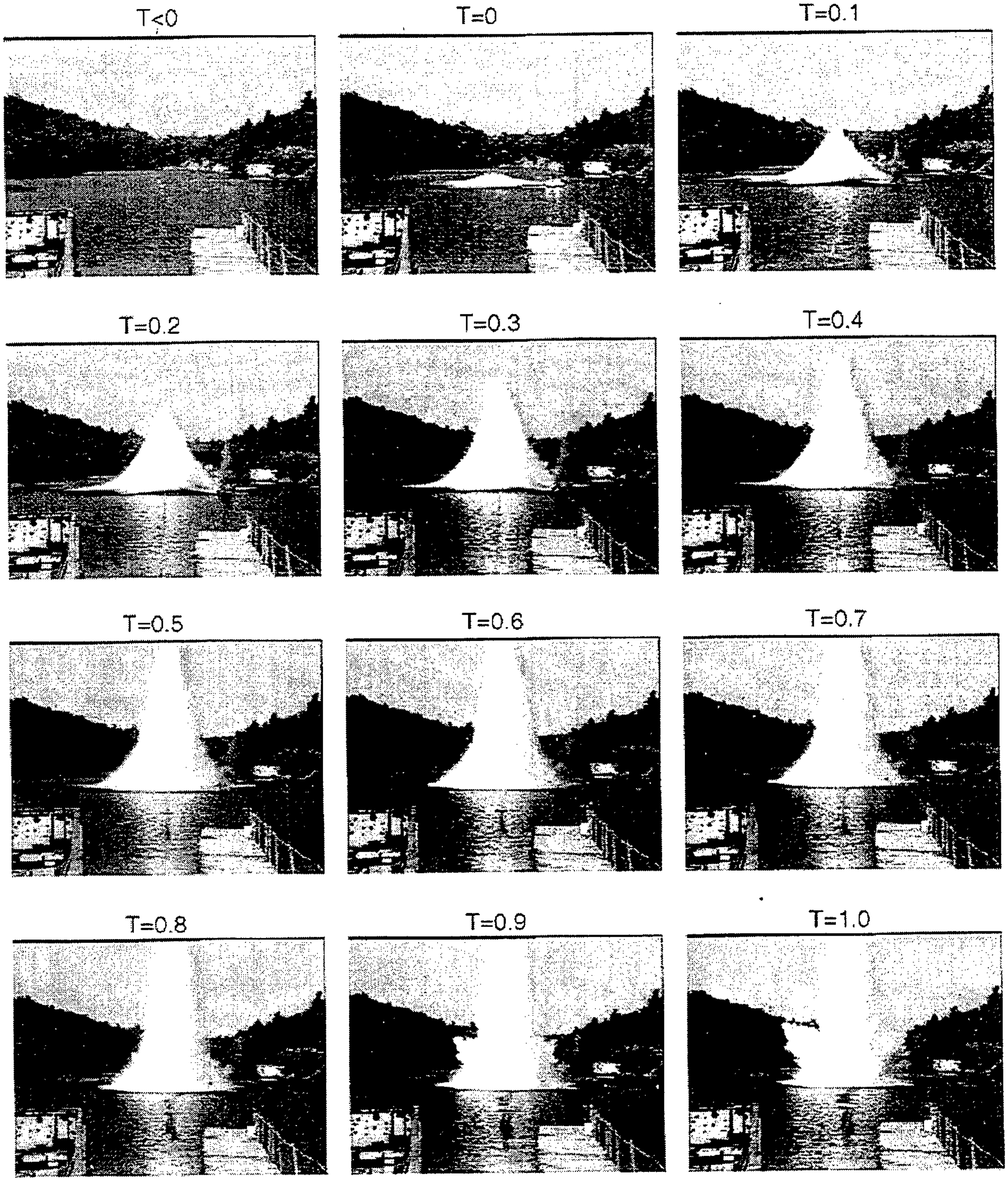


FIGURE 4. DISCRETE LINE CHARGE, SIDE VIEW

TEST DETAILS

CHARGE CONFIGURATIONS

The line charges were constructed from 1.25 lb M113 Composition C-4 demolition blocks extended along a line at a relatively shallow firing depth. Each scaled charge was initiated from the surface end of 50-gr/ft detonating cord that ran from a surface float down to and along the line of C-4. A knot in the detonating cord was embedded in each C-4 charge to ensure detonation coupling.

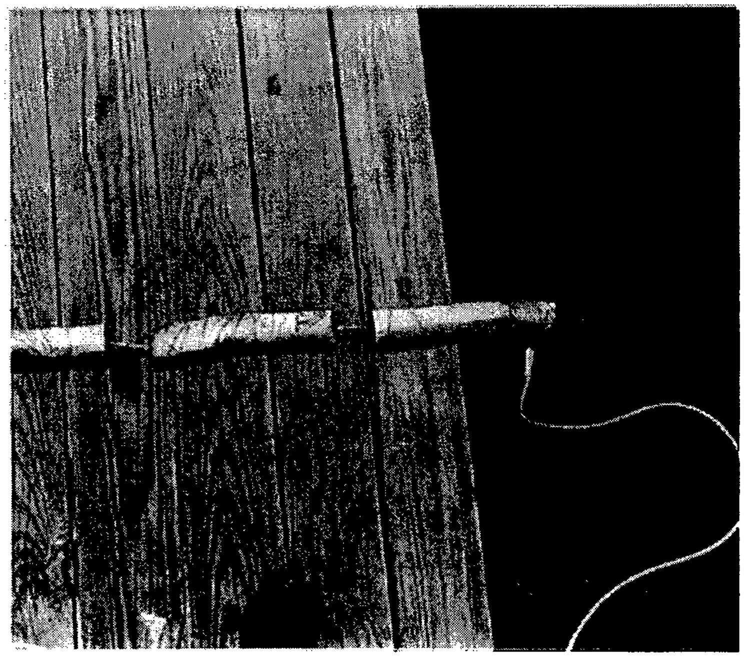
The following two line charge configurations were examined:

- Continuous: A continuous line charge configuration is depicted in Figure 5. Single C-4 M113 demolition blocks were split lengthwise and fastened around a length of ¼-in. steel rod along which the detonating cord also was fastened. The 10-in. blocks were placed end-to-end with 2-in. gaps between blocks (see Figure 5a). The rod was supported by several vertical lines suspended from PVC pipe on the water surface to support the underwater line charge at the desired depth along a horizontal line (see Figure 5b). Figure 5c illustrates the continuous line charge set-up in the water. The arrow denotes the direction from which the detonation begins.

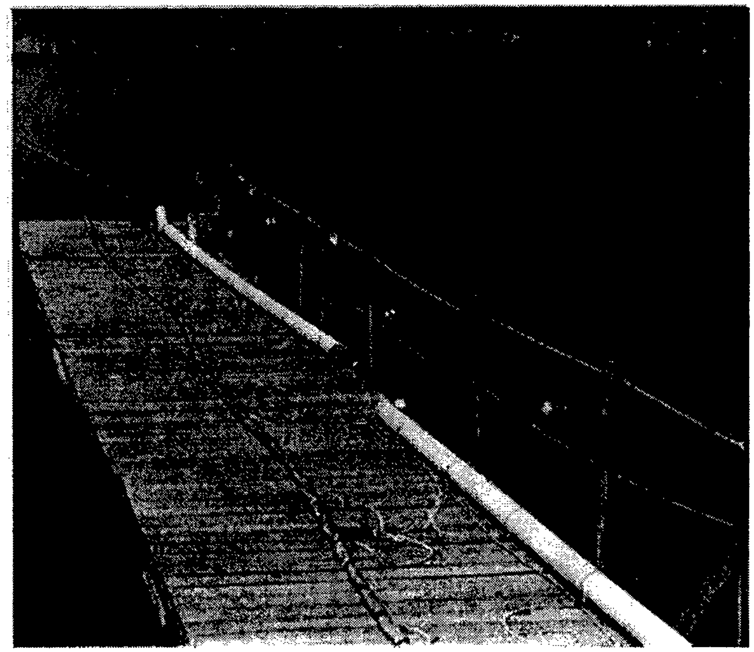
- Discrete: A discrete line charge is depicted in Figure 6. Separate charges, each weighing 10 lb, were fabricated on-site from eight, 1.25-lb, C-4 M113 demolition blocks. These charges were suspended from surface floats at horizontal separations approximating the firing depth (see Figure 6b). Detonating cord was strung from the surface down to and along the string of charges so that the time interval between detonations was determined by the detonation velocity in the detonating cord. This time interval is a few hundred microseconds. Figure 6c illustrates the discrete line charge setup in the water.

The following two parameters have been used to characterize the tests:

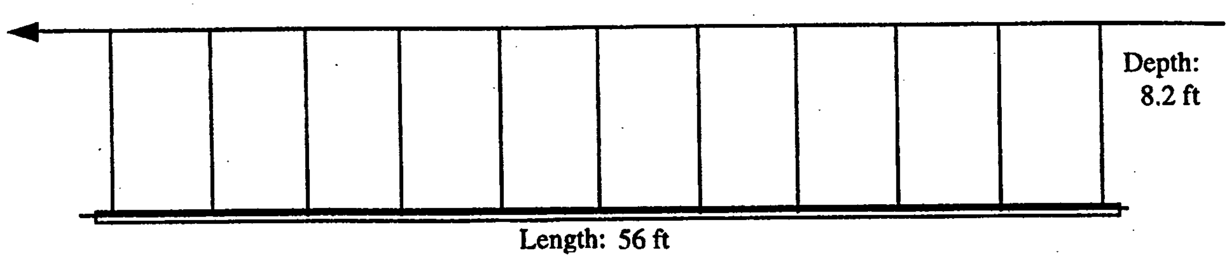
- Charge weight per unit length: For a continuous line charge, the calculation of this parameter is the ratio of total charge weight to total line length. For the discrete charges at uniform separation, this parameter is the ratio of individual charge weight to the separation length between charges. For the discrete line charges fired at varying horizontal separations, this parameter is calculated as follows:



a. C-4 Blocks

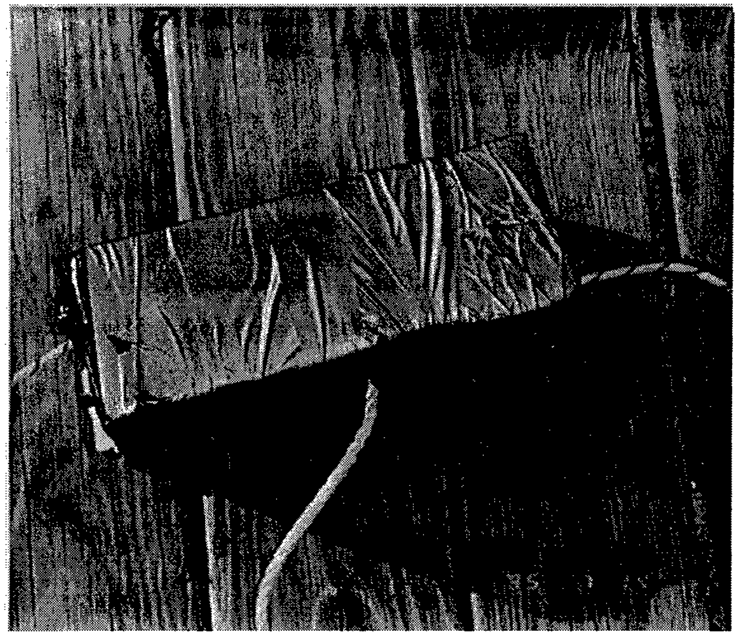


b. Line Charge Support

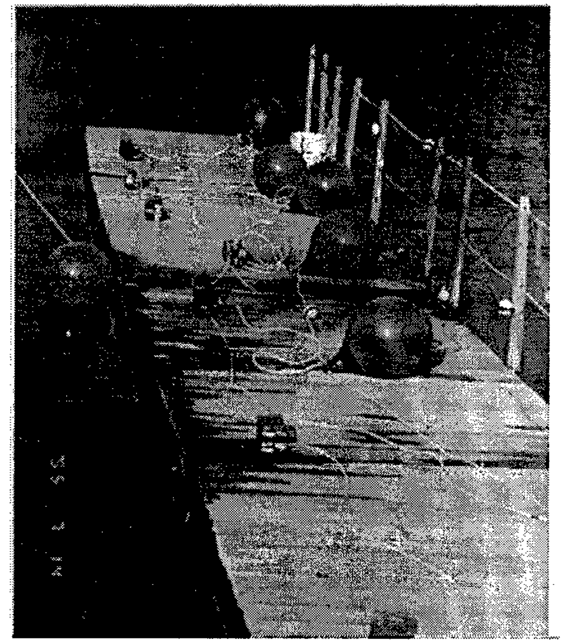


c. Test Setup

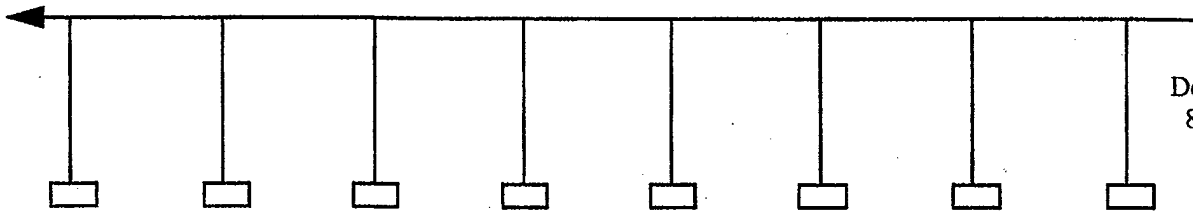
FIGURE 5. CONTINUOUS LINE CHARGE CONFIGURATION



a. 10-lb C-4 Charge



b. Line Charge Support



c. Test Setup

FIGURE 6. DISCRETE LINE CHARGE CONFIGURATION

$$\frac{(\textit{Total Number of Charges} - 1) * (\textit{Single Charge Weight})}{\textit{Total Charge Length Projected on Surface}}$$

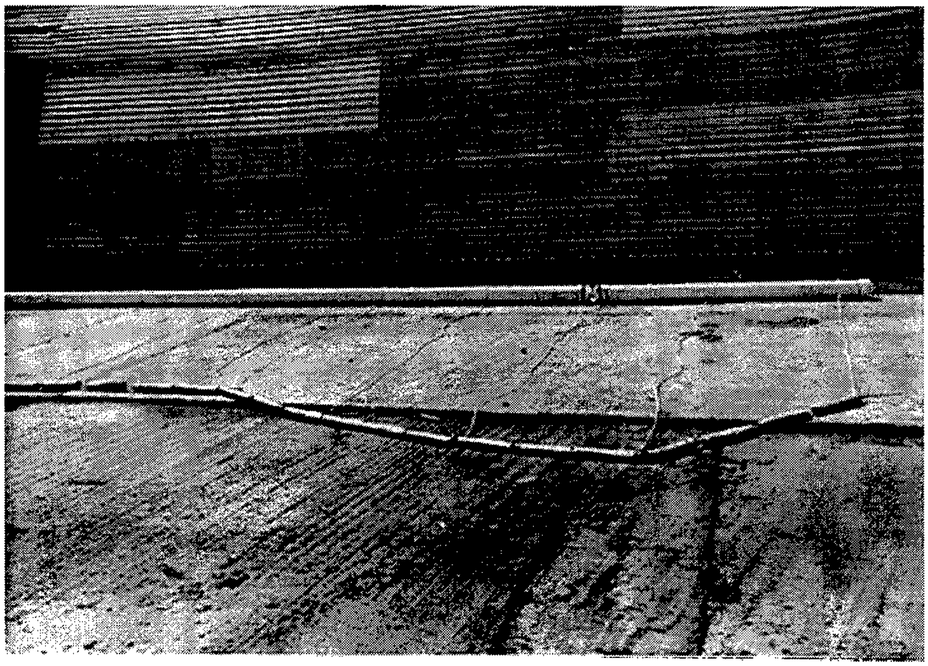
- Bubble aspect ratio: This quantity is the ratio of line charge length (L) to maximum diameter (D) of the cylindrical bubble produced by a uniform line charge fired at the same depth. The bubble diameter was extrapolated from data obtained on other tests using detonating cord containing a variety of materials. When this ratio approaches unity, the bubble shape approaches that of a sphere, and the resultant line charge plume resembles those generated by a concentrated single charge. However, at unity, the bubble is not strictly a sphere since the calculation does not account for the horizontal expansion of the bubble at either end of the line charge.

The following two depth arrangements were chosen for firing these line charge tests:

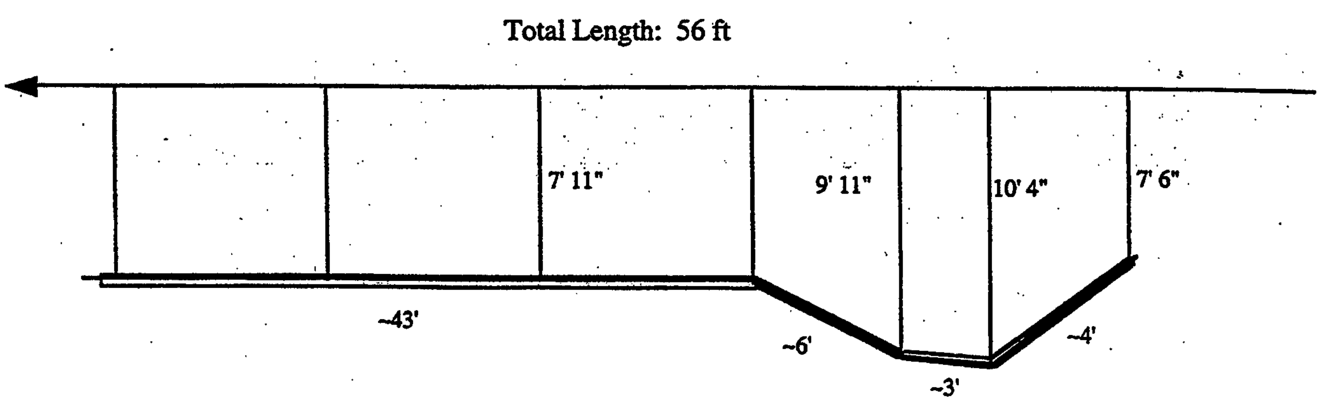
- Ideal Depth: All of the charges were fired at a predetermined depth; these conditions mimic an idealized laboratory-like configuration. Each line charge is assumed to be located at a definite position under a perfectly flat water surface (see Figures 5c and 6c).

- Predicted Depths: For the continuous line charge, the steel rod to which the continuous charges were taped was bent to match the configuration predicted by a computer model of the anticipated deployment system.[4] Figure 7 depicts the configuration of the continuous line charge setup at varying depths. For the discrete line charge, each discrete charge was placed at the depth and separation from its adjacent charge that was determined by the modeling program. Figure 8 depicts the configuration of the discrete line charge setup at varying depths. As a dividend, these line charge arrangements also mimic the effect of having the charges located under a water surface that is churned by random sea waves.[3]

Characteristics of the 13 shots fired in this test series are listed in Table 1. The third column lists the depths at which the line charges were detonated. In this column, "Pred" (i.e., "predicted") symbolizes that the entire line charge was not at the same depth. "Pred" indicates that the line charge is placed at varying depths as predicted by the computer model for a deployed line charge. In the fourth column, the numbers in parentheses are the number of individual demolition blocks that were used to fabricate the respective continuous line charges. Each of the discrete line charges consisted of a number of distinct charges each weighing 10 lb. Charge separation is the spacing between individual charges in the discrete line charge. Total weight and length refer to the total amount of explosive that was distributed between the ends of each line charge. Charge density is the charge weight per unit length: the ratio of the preceding two columns. The last column, titled "L/D," is the bubble aspect ratio determined as previously described.

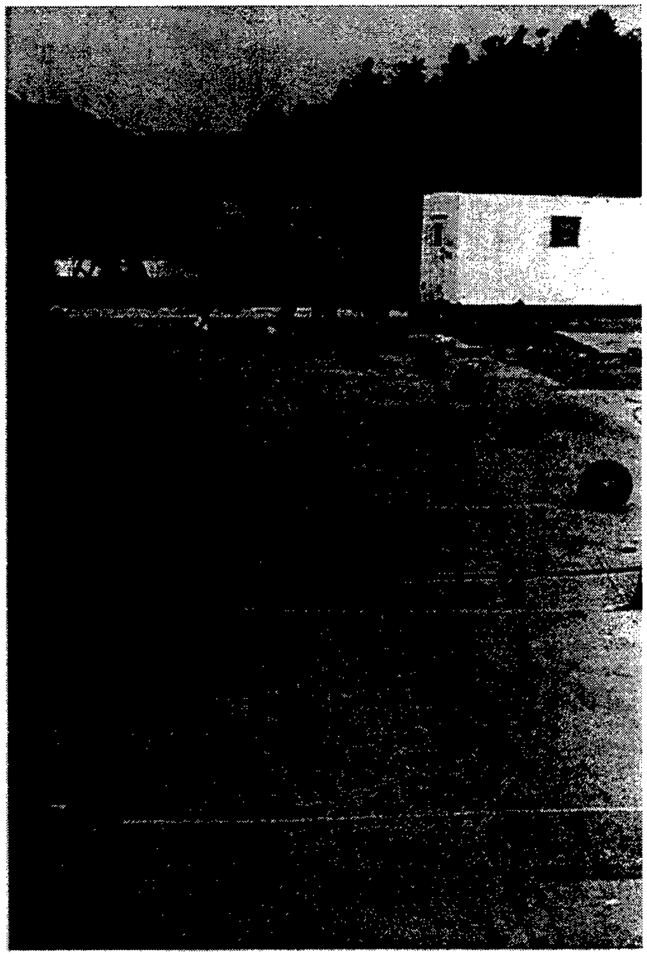


a. Line Charge Arrangement

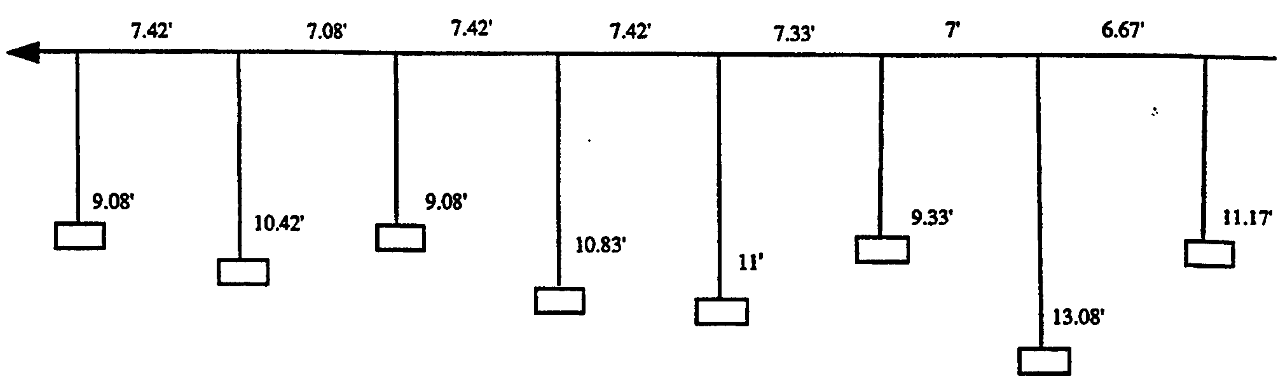


b. Test Setup

FIGURE 7. CONTINUOUS LINE CHARGE AT VARYING DEPTHS



a. Line Charge Arrangement



b. Test Setup

FIGURE 8. DISCRETE LINE CHARGE AT VARYING DEPTHS

TABLE 1. SHOT LOG

Shot	Type	Depth (ft)	No. Of Charges	Charge Separation (ft)	Total Weight (lb)	Length (ft)	Charge Density (lb/ft)	L/D
1	Discrete	12.6	8	3	80	21.0	3.33	0.58
2	Discrete	8.2	5	8	50	32.0	1.25	1.37
3	Discrete	Pred	6	7 to 7.5	60	35.8	1.40	1.53
4	Continuous	8.2	(20)	---	25	20.0	1.25	0.84
5	Discrete	Pred	9	2.25 to 2.75	90	20.1	3.98	0.56
6	Discrete	8.2	8	8	80	56.0	1.25	2.40
7	Continuous	8.2	(56)	---	70	56.0	1.25	2.40
8	Continuous	Pred	(56)	---	70	53.7	1.30	2.30
9	Discrete	8.2	5	8	50	32.0	1.25	1.37
10	Discrete	9.4	5	8	50	32.0	1.25	1.37
11	Continuous	9.4	(40)	---	50	40.0	1.25	1.70
12	Discrete	6.8	5	8	50	32.0	1.25	1.37
13	Discrete	Pred	8	6.75 to 7.4	80	50.3	1.39	2.10

For this test series, the charge density of the charges used on Shots 1 and 5 was more than twice that of the charges used on the other shots. In addition, these two shots, as well as Shot 4, were fired at depths less than the anticipated cylindrical bubble diameter. (The predicted bubble aspect ratio was less than unity.) As expected, these line charge configurations did not produce plumes high or dense enough for the intended use of the final device. Since the other 10 line charges produced plumes of sufficient dimensions to form an effective wall of water, these three shots will not be included in the following discussion. For the remaining 10 shots, the linear charge density fell between 1.25 and 1.68 lb/ft, and the bubble aspect ratio was greater than 1.3.

CHARGE DEPLOYMENT

The plan view layout for the test series is shown in the survey coordinates of the DTI quarry in Figure 9. The numbers adjacent to several of the points on the sketch are arbitrary identification numbers assigned by the survey team. The rigging was designed to ensure that the center of each line charge was placed at the same location relative to the video cameras, the microwave beam, and the conductivity probe line for each shot. This point is labeled "15," as well as "SZ," to represent Surface Zero. Fixed lengths of polypropylene line were attached to points 12 and 14 on the edge of the quarry; these lines joined at point 16, from which a breakaway line was attached to one end of the line charge surface line. The other end of the line charge surface line was attached to point 7 in front of camera 2. Replacing the breakaway surface line for each shot and pulling the rigging taut placed each line charge arrangement in the same location, so that the cameras, microwave towers, and conductivity probes (points 6 and 8 on the survey) could remain fixed. Figure 10 shows the elevation view of the test setup.

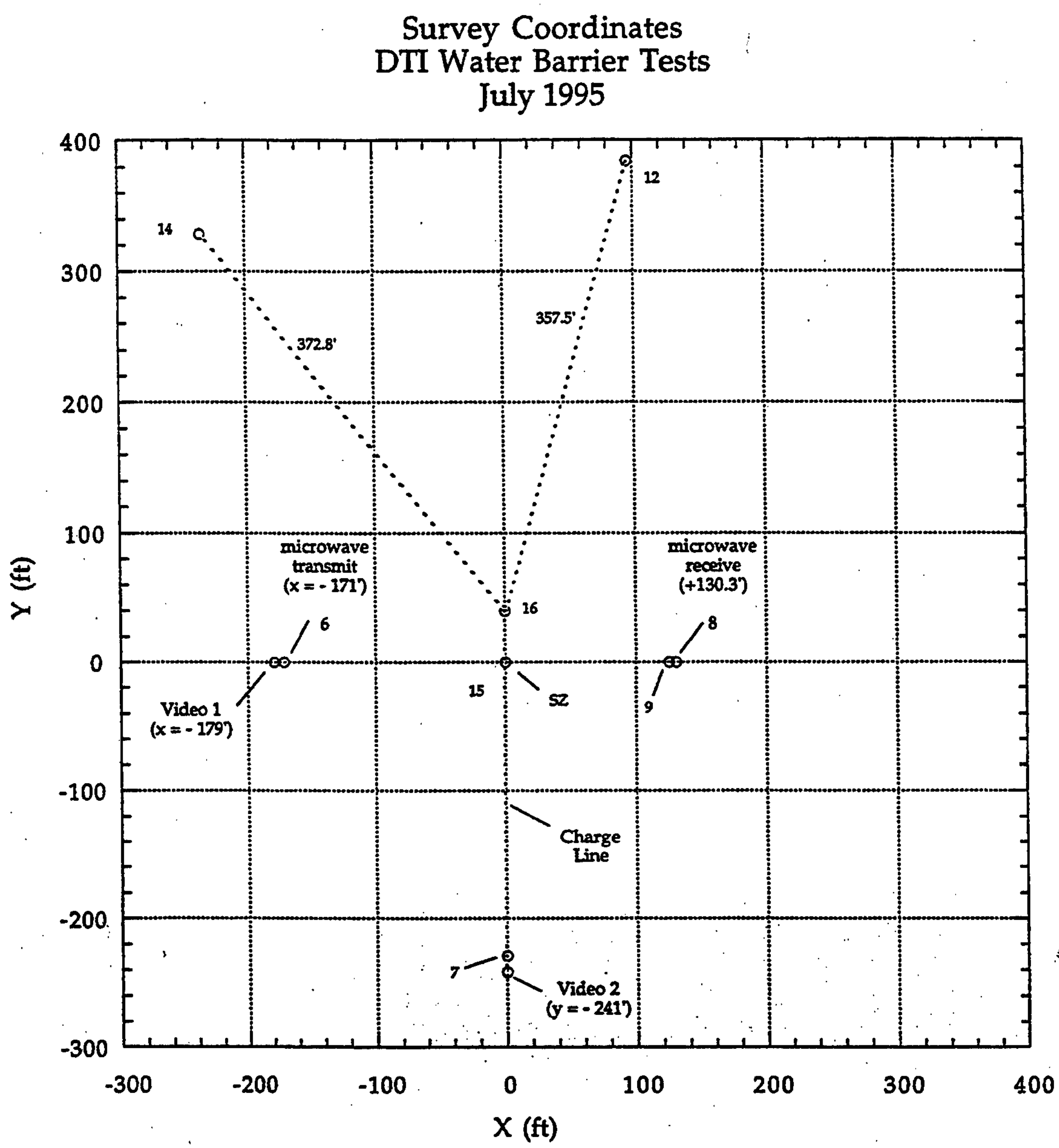


FIGURE 9. PLAN VIEW OF TEST SETUP

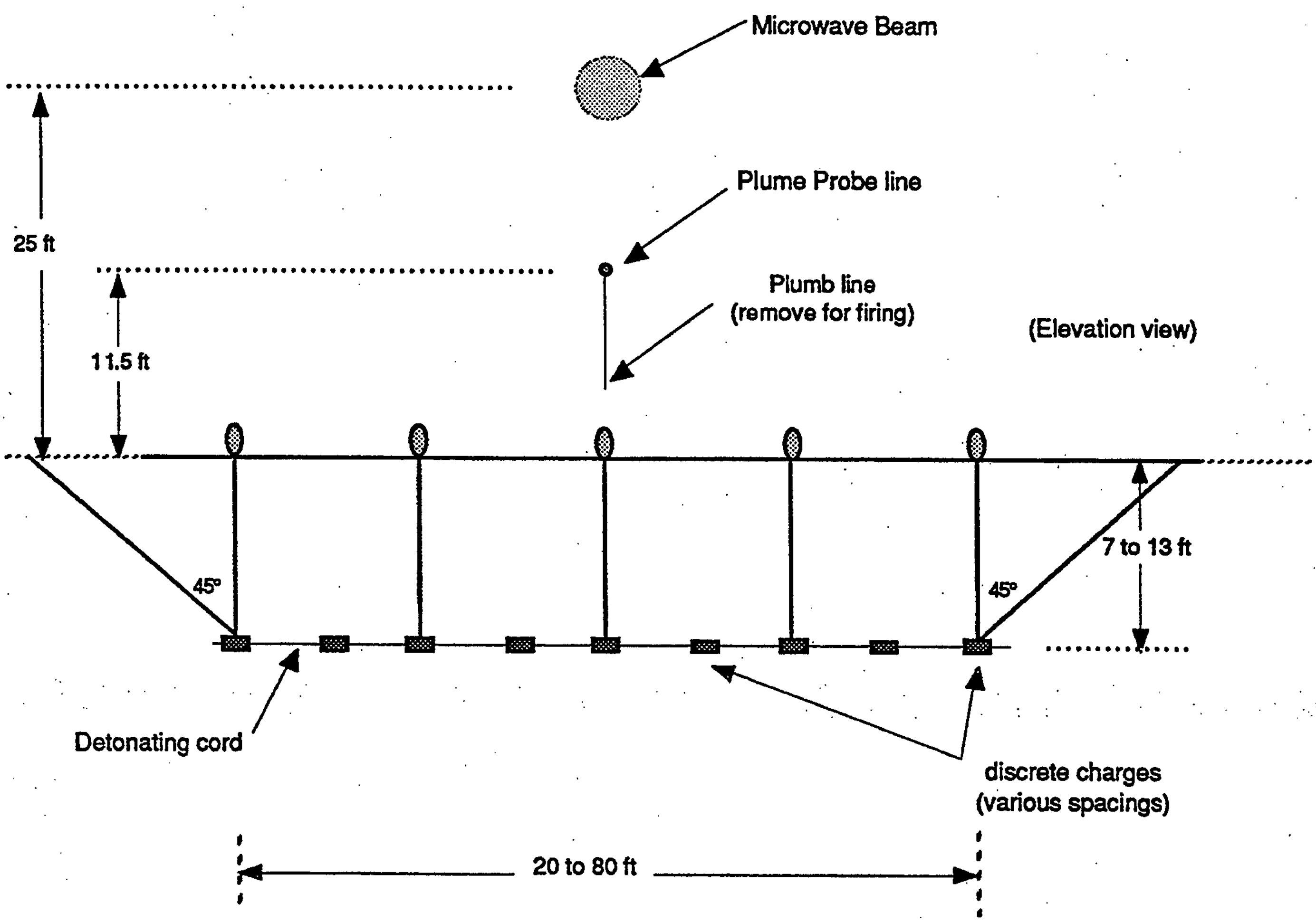


FIGURE 10. ELEVATION VIEW OF TEST SETUP

WATER DENSITY MEASUREMENT TECHNIQUES

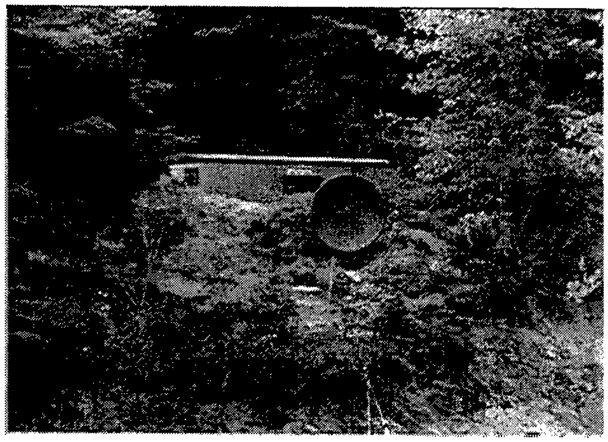
INTRODUCTION

A key element in the development and evaluation of the Water Barrier Ship Self Defense Concept, as well as the validation of a Water Barrier hydrodynamic plume model, is the determination of the total water mass confined within the barrier plume cross section. Since no previous data exist for the direct measurement of the water mass in a plume, two complimentary measurement techniques have been designed, fabricated, and successfully used in underwater explosion experiments by NSWCDD.[8] One method measures the attenuation of a microwave beam after it has propagated through the barrier plume cross section. The attenuation characteristic of the microwave beam within the plume depends only on the macroscopic volume ratio of the water-to-air mixture. This ratio is used, in turn, to derive the water density.[9] Another method uses multiple electrical conductivity probes that are suspended within the plume cross section. Each probe measures the conductivity of the medium between two rods and is thus calibrated using the fractional water density between the rods.[10]

MICROWAVE ABSORPTION

One technique to determine the amount of water within a barrier plume is based on the attenuation characteristics of a microwave beam that has propagated through the plume cross section. The attenuation coefficient can be obtained by measuring the amplitude of the wave after the microwave beam has traversed the plume cross section. This information can then be used to derive the water density since the attenuation characteristics depend only on the macroscopic volume ratio of water to air. Choe et al.[8-9] describe the theory of relating the water density of a plume to the microwave attenuation rate. This theory is presented along with the experimental results from previous field tests. A frequency of 4 GHz was chosen based on the following parameters: attenuation rate of the microwave beam within the plume, practical size of antennas, propagation range, cost, and availability of equipment.

As shown in Figures 11a and 11b, the transmitting and receiving antennas were placed perpendicular to the charge line so that the microwave beam propagates through the scaled barrier plume cross section at a height of 25 ft above the water surface. The two antennas were separated by a distance of approximately 300 ft with the charge line centered at approximately the halfway point. Both antennas were identical parabolic dishes with a diameter of 6.0 ft and a gain of 35.0 dBi. The transmitter used a pulsed, traveling wave tube amplifier (TWTA) to boost the 4-GHz microwave signal to 1 kW prior to transmission. A pulse width of 10 μsec with a repetition frequency of 1 kHz was employed to allow a more-than-adequate sampling rate relative to the motion of the plume. Timing control was accomplished using a pulse generated at



a. Transmitting Antenna

b. Receiving Antenna

c. Microwave Equipment

FIGURE 11. MICROWAVE SETUP

the transmitter via direct cable link to the receiver. The receiving antenna fed the attenuated signal into a system that was capable of a 111-dB dynamic range. The receiver consisted of two direct logarithmic video amplifiers (DLVA), with each DLVA operating in a different power band. The microwave receiving equipment is displayed in Figure 11c. The resulting signal was amplified and buffered before being recorded by a data acquisition system as a function of time.

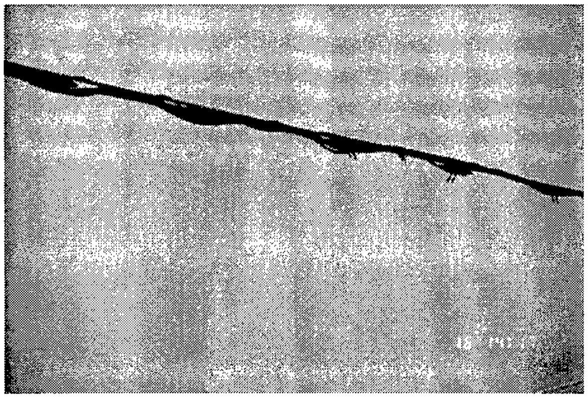
ELECTRICAL CONDUCTIVITY

Another water density measurement technique measures the electrical conductivity of the water that is present in the gap between two conducting rods. A conductivity probe set consists of two ¼-in. stainless steel rods that are 1 ⅜-in. long and are spaced ¾-in. apart. The outer side of each rod is painted to limit the response to only the region located between the rods. The rods are secured in position with a molded epoxy power line splice, which results in a rugged device that can be easily attached to a rope or cable that is suspended and stretched over the water surface.

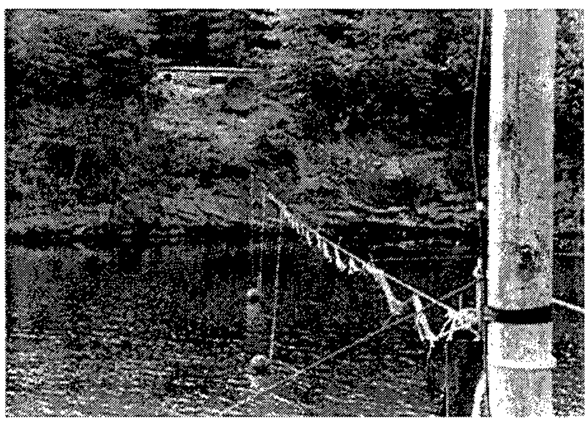
The two rods are connected through a coaxial cable to a resistor, a signal generator, and an output recorder. The setup is a simple voltage divider and the output measures the voltage across the rods. The output voltage changes depending on the conductivity between the rods, which in turn changes with the amount of water between the rods. The probe therefore provides information on the water density at the position where the probe is located. The judicious placement of multiple probe sets within the barrier plume cross section provides spatial and time resolved water density measurements. Lipton[10] describes the theory of relating the water density of a barrier plume cross section to the electrical conductivity of water, along with the experimental results from previous field tests.

Certain limitations are intrinsic to this probe design. The conductivity probe system assumes that the water droplets in the plume are comparable in size to the gap between the rods. While a significant amount of water may be present within the plume, any water droplets smaller than the rod spacing will not indicate any conductivity. Furthermore, any twist in the support line that cause the probes to point upward will cause "shadowing" of the rising plume by the probe body. Therefore, these limitations will cause the probe sets to underestimate the amount of water density that is present at the probe locations within the plume.[7,10]

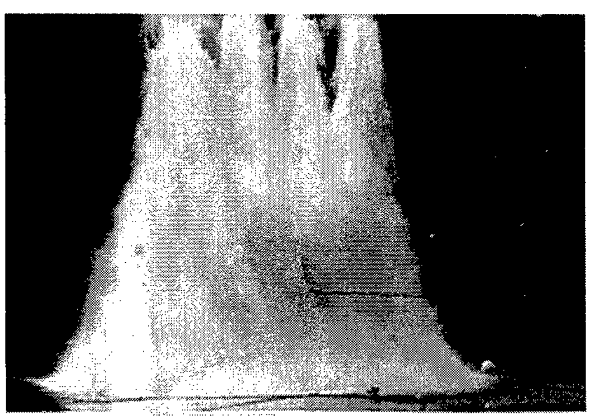
For these tests, fifteen conductivity probe sets were spaced 1 ft apart and attached to a steel cable as shown in Figures 12a and 12b. The steel cable with the probe sets is tautly stretched across the quarry pond to reduce probe motion caused by the impact of the barrier plume. The taut steel cable with the probe sets is positioned perpendicular to the charge line and parallel to the microwave beam at a height of 11.5 ft above the water surface. The charge line is centered beneath the probe line at approximately the halfway point. Figure 12c shows the conductivity probe line positioned perpendicular to the developing barrier plume cross section.



a. Conductivity Probes Close View



b. Conductivity Probe Line



c. Conductivity Probe Line in Plume

FIGURE 12. CONDUCTIVITY PROBE SETUP

EQUIVALENT WATER LENGTH

In order to compare the recorded experimental results from each measurement technique and eventually with the hydrodynamic plume model, the density measurements are converted to a quantity defined as the equivalent water length (EWL) of 100 percent water. For the microwave measurements, the water volume ratio V_w within the cylindrical region of the microwave beam is calculated from the received power and the plume length L as a function of time.

$$EWL = V_w L$$

corresponds to the length of 100 percent water filling the cylinder having an equivalent mass as the plume at time t.

At any given time, each probe provides a value of water density fraction that equals the density of water in the region of the probe divided by 100 percent density and is a dimensionless number. Since the conductivity probes are located at discrete points, a trapezoidal rule integration is used to determine the measured EWL as a function of time. That is,

$$EWL = S_p[\frac{D_1}{2} + \sum_{i=2}^{n-1} D_i + \frac{D_n}{2}]$$

where S_p is the uniform spacing between the n probes, and D_i is the density fraction at the ith probe location.

RESULTS

DATA REDUCTION

The EWL was calculated from the microwave absorption and electrical conductivity density measurements of the water barrier plumes generated from scaled continuous and discrete line charges in the 1995 DTI test series. The microwave measurements are taken at a barrier plume cross section height of 25 ft and the conductivity probe measurements are taken at a height of 11.5 ft. In addition, the total time or the time duration that the EWL is equal to or above a specific value (EWL Total Time) was calculated from the microwave absorption and electrical conductivity density measurements. As previously indicated, Shots 1, 4, and 5 did not produce adequate plumes and are not included in this discussion.

For this discussion, 10 shots were reduced and have been grouped to simplify the analysis of the data. There is some necessary overlapping of the shots in the groupings.

- An overall perspective of the test series is provided by the first group of shots. Four shots (6, 7, 8, and 13) were considered together since they incorporate the effects of explosive line charge distribution and detonation depth variations.

- The effects of varying the detonation depth are examined both for continuous line charges (Shots 7 and 11) and for discrete line charges (Shots 9, 10, and 12).

- The effects of varying line charge length are illustrated for "ideal" discrete line charges by Shots 6 and 9 and for "predicted" discrete line charges by Shots 3 and 13.

- Repeatability of the line charge plume phenomena is also examined for discrete charges by comparing Shots 2 and 9.

- Finally, the effect of sequential versus simultaneous detonation of discrete charges on the resultant plume is examined. This was done by comparing Shot 9 (sequential detonation) from this test series with Shot 3 (simultaneous detonation) from a test series conducted in the Hi Test Laboratories (HTL) quarry at Arvonia, Virginia in the summer of 1993. Since the charge weights and explosives were the same on both series of tests, a direct comparison is meaningful. However, note that there is no accepted method for scaling the plumes produced by different charges or charge configurations to a common basis.

LINE CHARGE DISTRIBUTION EFFECT

Shots 6, 7, 8, and 13 represent the differing effects of the continuous and the discrete line charge configurations as well as the differences between "ideal" and "predicted" detonation depths. Table 2 lists the line charge configurations and characteristics for these series of shots. Shots 6 and 13 are discrete line charges and Shots 7 and 8 are continuous line charges. All are long enough (≥ 50 ft) to allow a wall of water to form over the central portion of the line charge length that is expected to be independent of any end effects.

The effects of changing various parameters are investigated by pairing the shots as follows:

- Shot 6 vs. Shot 7: Continuous versus discrete line charge at the "ideal" detonation depth
- Shot 6 vs. Shot 13: Discrete line charge at "ideal" versus "predicted" detonation depths; constant explosive weight
- Shot 7 vs. Shot 8: Continuous line charge at "ideal" versus "predicted" detonation depths; constant explosive weight
- Shot 8 vs. Shot 13: Continuous versus discrete line charge at "predicted" detonation depths

Figure 13 compares the EWL and the EWL Total Time of the plumes generated from the discrete (Shot 6) and continuous (Shot 7) line charges based on the conductivity and microwave measurements. The line charges are fired at the previously defined "ideal" detonation depth of 8.2 ft. Figure 13a shows the conductivity EWL as a function of time along the probe line for the fifteen probes within the plume at the barrier cross section height of 11.5 ft. The discrete line charge plume shows two distinct EWL peaks at 0.6 and 1.6 sec. The first EWL peak of 2.3 ft occurs at the time that the secondary plumes reach a height of 11.5 ft. The second peak at 1.6 sec reaches a maximum EWL of 5.6 ft. The continuous line charge plume shows the same type of distinctive EWL peaks at 0.8 and 1.2 sec. The first EWL peak of 2.2 ft for the continuous line charge plume occurs at the time that the secondary plumes reach a height of 11.5 ft, while the second peak at 1.2 sec shows a maximum EWL of 3.8 ft.

Even though the maximum conductivity EWL for the discrete line charge plume is approximately 1½ times the maximum EWL for the continuous line charge plume, the maximum EWL magnitudes do not provide a sense of the quantity of water within the plume over a period of time at a particular cross section height. To compare the amount of water generated from a particular line charge configuration, the total time that the EWL is equal to or greater than a specific quantity (EWL Total Time) is calculated for each configuration. Figure 13b shows the conductivity EWL Total Time for the plumes of a discrete and continuous line charge detonated at the "ideal" depth. The period of time that the conductivity EWL for the discrete line charge plume is equal to or greater than 1 ft is about 1 sec, as compared to 0.9 sec for the continuous line

TABLE 2. LINE CHARGE DISTRIBUTION EFFECT SHOT CHARACTERISTICS

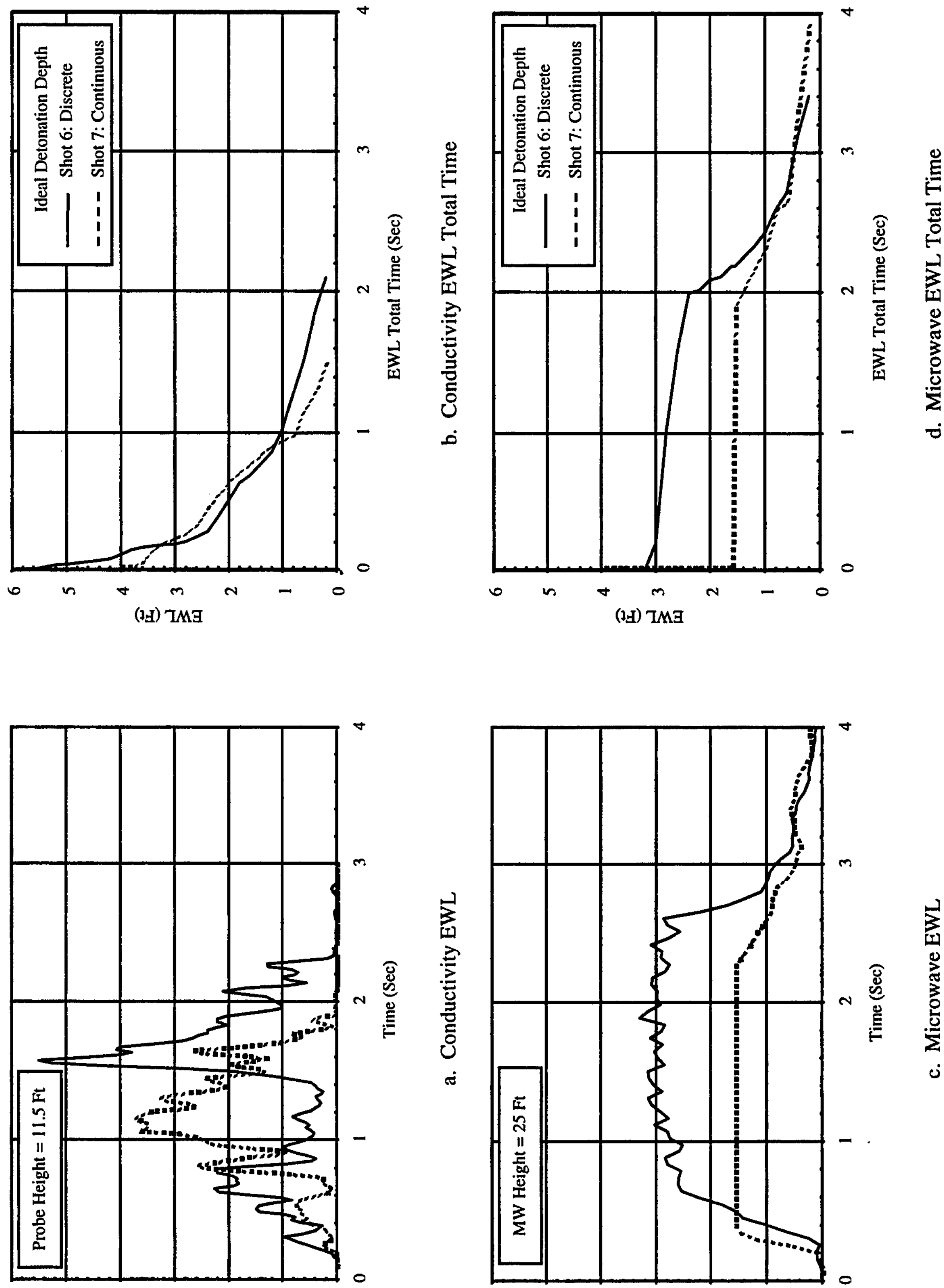
Shot	Type	Depth (ft)	No. Of Charges	Charge Separation (ft)	Total Weight (lb)	Length (ft)	Charge Density (lb/ft)	L/D
6	Discrete	8.2	8	8	80	56.0	1.25	2.40
7	Continuous	8.2	(56)	---	70	56.0	1.25	2.40
8	Continuous	Pred	(56)	---	70	53.7	1.30	2.30
13	Discrete	Pred	8	6.75 to 7.4	80	50.3	1.39	2.10

charge plume. In fact, a comparison of the two curves shows minimal-to-no difference for the conductivity EWL duration between 1 and 3 ft.

Figure 13c shows the microwave EWL as a function of time within the cylindrical region of the microwave beam at the barrier cross section height of 25 ft. The microwave data for the continuous line charge plume were truncated at an EWL of 1.55 ft because of a failure in the second DLVA in the microwave receiver. The discrete line charge plume reaches a maximum of 3.4 ft. Figure 13d shows that the discrete line charge plume has an EWL Total Time of about 2 sec for an EWL of 2.5 ft or greater. Since the EWL data for the continuous line charge plume are truncated at 1.55 ft, a comparison of the EWL Total Time at this value shows the discrete line charge plume with a duration of 2.2 sec as compared to 1.9 sec for the continuous line charge plume. A comparison of the two curves in Figure 13d seem to indicate that perhaps the discrete line charge plume has a longer microwave EWL Total Time duration than the continuous line charge plume.

Caution should be exercised in attempting to compare the EWL magnitudes between the microwave and conductivity measurements. As previously stated, certain limitations are intrinsic to the electrical conductivity measurements that use this probe design. The conductivity probe system assumes that the water droplets in the plume are comparable in size to the gap between the rods. While a significant amount of water may be present within the plume, any water droplets smaller than the rod spacing will not indicate any conductivity. Furthermore, any twist in the support line that causes the probes to point upward will cause "shadowing" of the rising plume by the probe body. Therefore, these limitations will cause the probe sets to underestimate the amount of water that is present at the probe locations within the plume.[7,10] For these reasons and the fact that the measurements are taken at different barrier cross-section heights, comparisons between the two measurement techniques are not made.

Figure 14 compares the EWL and the EWL Total Time for the discrete line charge plume fired at the "ideal" (Shot 6) and "predicted" (Shot 13) detonation depths. The total weight of the C-4 explosive remains constant at 80 lb for both line charge configurations. The "predicted" depth and spacing of the discrete charges are depicted in Figure 8. Figure 14a shows that the "ideal" discrete line charge plume reaches a maximum conductivity EWL of 5.6 ft at 1.6 sec after detonation. Furthermore, the "predicted" discrete line charge plume reaches a maximum EWL of 6.6 ft at 1.4 seconds. In Figure 14b, the EWL Total Time indicates that more water is present in



a. Conductivity EWL

b. Conductivity EWL Total Time

c. Microwave EWL

d. Microwave EWL Total Time

FIGURE 13. COMPARISON OF IDEAL DISCRETE AND CONTINUOUS LINE CHARGES

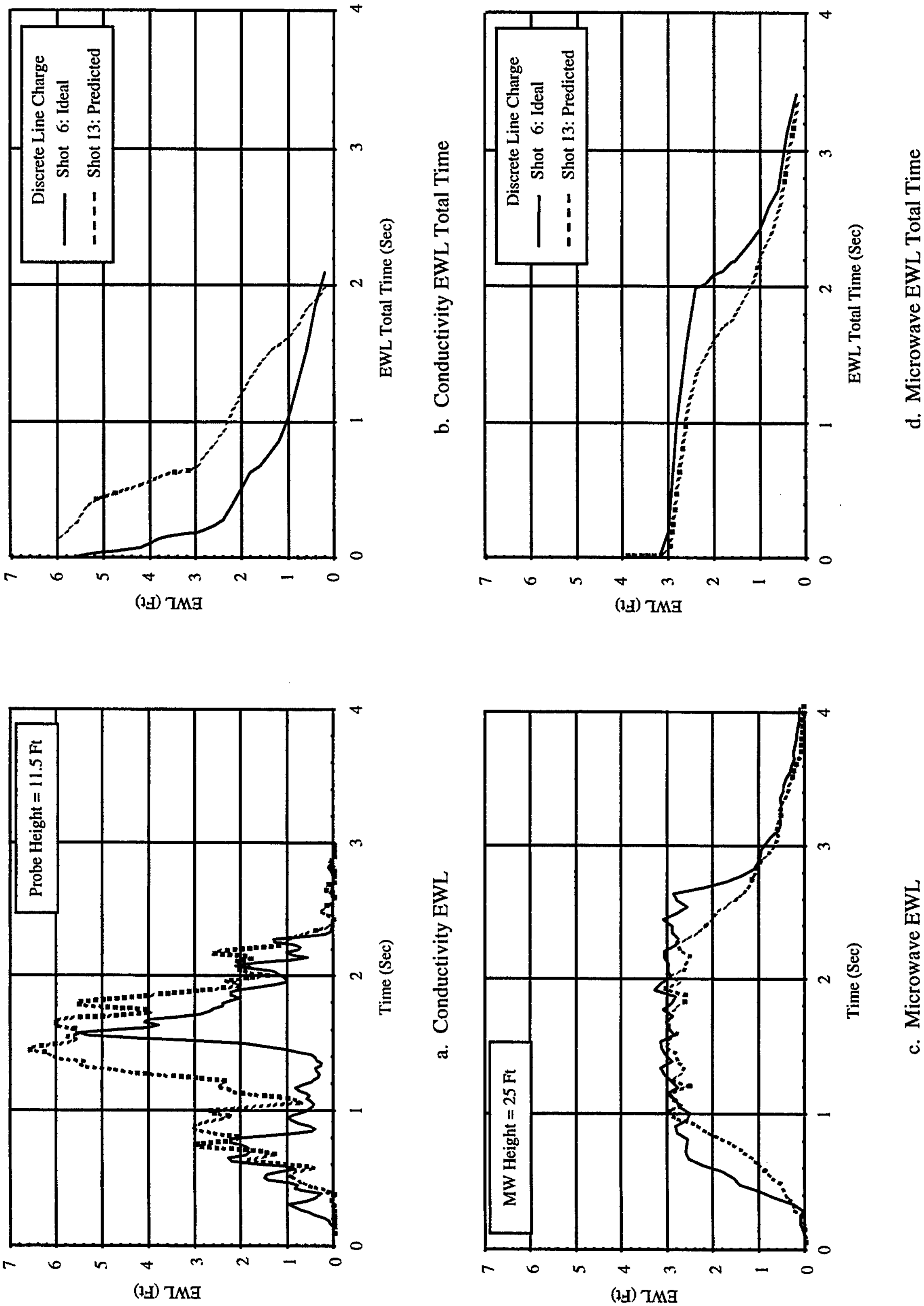


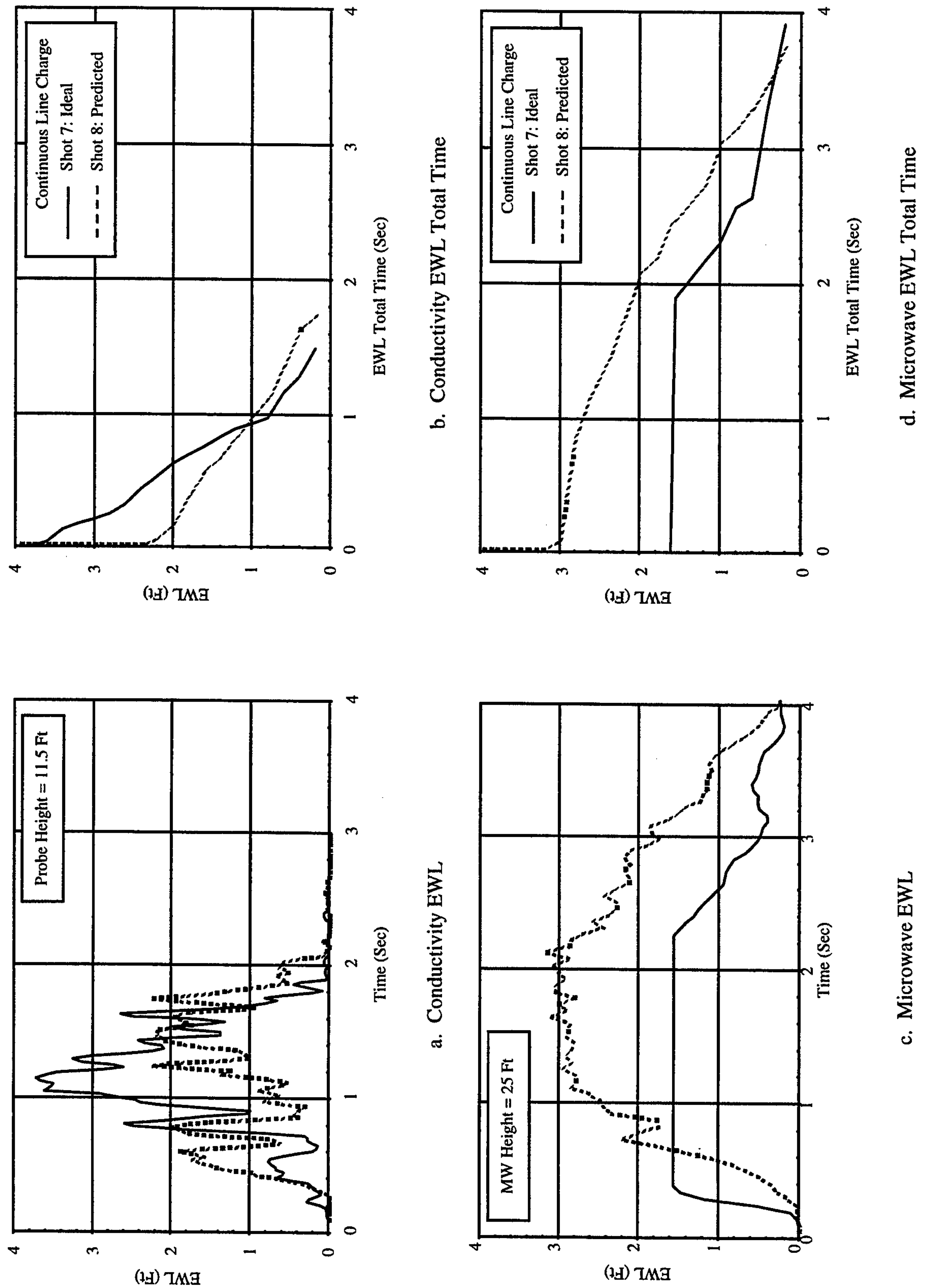
FIGURE 14. COMPARISON OF IDEAL AND PREDICTED DISCRETE LINE CHARGES

the "predicted" discrete line charge plume at a height of 11.5 ft than in the "ideal" discrete line charge plume. However, the microwave data in Figures 14c and 14d indicate that the "ideal" discrete line charge plume has a longer duration for a microwave EWL of 2 ft at a barrier cross-section height of 25 ft than the "predicted" discrete line charge plume.

Figure 15 compares the EWL and the EWL Total Time for the continuous line charge plume fired at the "ideal" (Shot 7) and "predicted" (Shot 8) detonation depths. The total weight of the C-4 explosive remains constant at 70 lb for both line charge configurations. The "predicted" depth of the continuous line charge plume is depicted in Figure 7. Figure 15a shows that the "ideal" continuous line charge plume reaches a maximum conductivity EWL of 3.8 ft at 1.2 sec after detonation. The "predicted" continuous line charge plume reaches a maximum conductivity EWL of 2.3 ft at 1.2 sec. In Figure 15b, the EWL Total Time indicates that more water is present in the "ideal" continuous line charge plume between an EWL of 1 to 3 ft at a height of 11.5 ft than in the "predicted" continuous line charge plume. However, the microwave data in Figures 15c and 15d indicate that the "predicted" continuous line charge plume may have slightly more water at a height of 25 ft than the "ideal" continuous line charge plume for a microwave EWL of 1.55 or less. The sense of the EWL Total Time curve for the "ideal" continuous line charge plume indicates more water for EWL greater than 1.55 ft. However, the magnitude of the amount of water present in the plume cannot be verified since the microwave data are truncated for Shot 7 because of equipment failure.

Figure 16 compares the EWL and the EWL Total Time for the discrete (Shot 13) and continuous (Shot 8) line charge plumes fired at their "predicted" detonation depths. Figure 16a shows that the "predicted" discrete line charge plume reaches a maximum conductivity EWL of 6.6 ft at 1.4 sec after detonation. The "predicted" continuous line charge plume reaches a maximum EWL of 2.3 ft at 1.2 sec. In Figure 16b the EWL Total Time indicates that more water is present in the "predicted" discrete line charge plume at a height of 11.5 ft than in the "predicted" continuous line charge plume. However, the microwave data in Figures 16c and 16d indicate that the "predicted" continuous line charge plume may have slightly more water at a height of 25 ft than the "predicted" discrete line charge plume for an EWL of 2.4 ft or less. The EWL Total Time curves for EWL greater than 2.4 ft match for the plume of both line charge configurations.

An EWL of 1.55 ft is chosen as the basis to summarize and compare the effect of the line charge distribution on the barrier plume for Shots 6, 7, 8, and 13. This value of EWL is chosen since the microwave EWL for Shot 7 is truncated at 1.55 ft. Figure 17 illustrates the EWL Total Time that the EWL is $\geq$1.55 ft based on the conductivity and microwave measurements for these shots. The maximum plume heights for these four line charge configurations are presented for comparative purposes.[11] From the conductivity measurements at the barrier cross section height of 11.5 ft, the duration for EWL $\geq$1.55 ft is around 0.7 sec. The "predicted" discrete line charge (Shot 13) plume has the longest EWL duration of 1.5 sec at this height. From the microwave measurements at the cross section height of 25 ft, the EWL duration is around 2 sec. The "predicted" continuous line charge (Shot 8) plume has the longest duration of 2.5 sec. Comparison of plume heights with the conductivity and microwave EWL Total Time durations indicate that plume heights do not necessarily correlate with the amount of water contained within the barrier plume at the cross section heights of 11.5 and 25 ft.



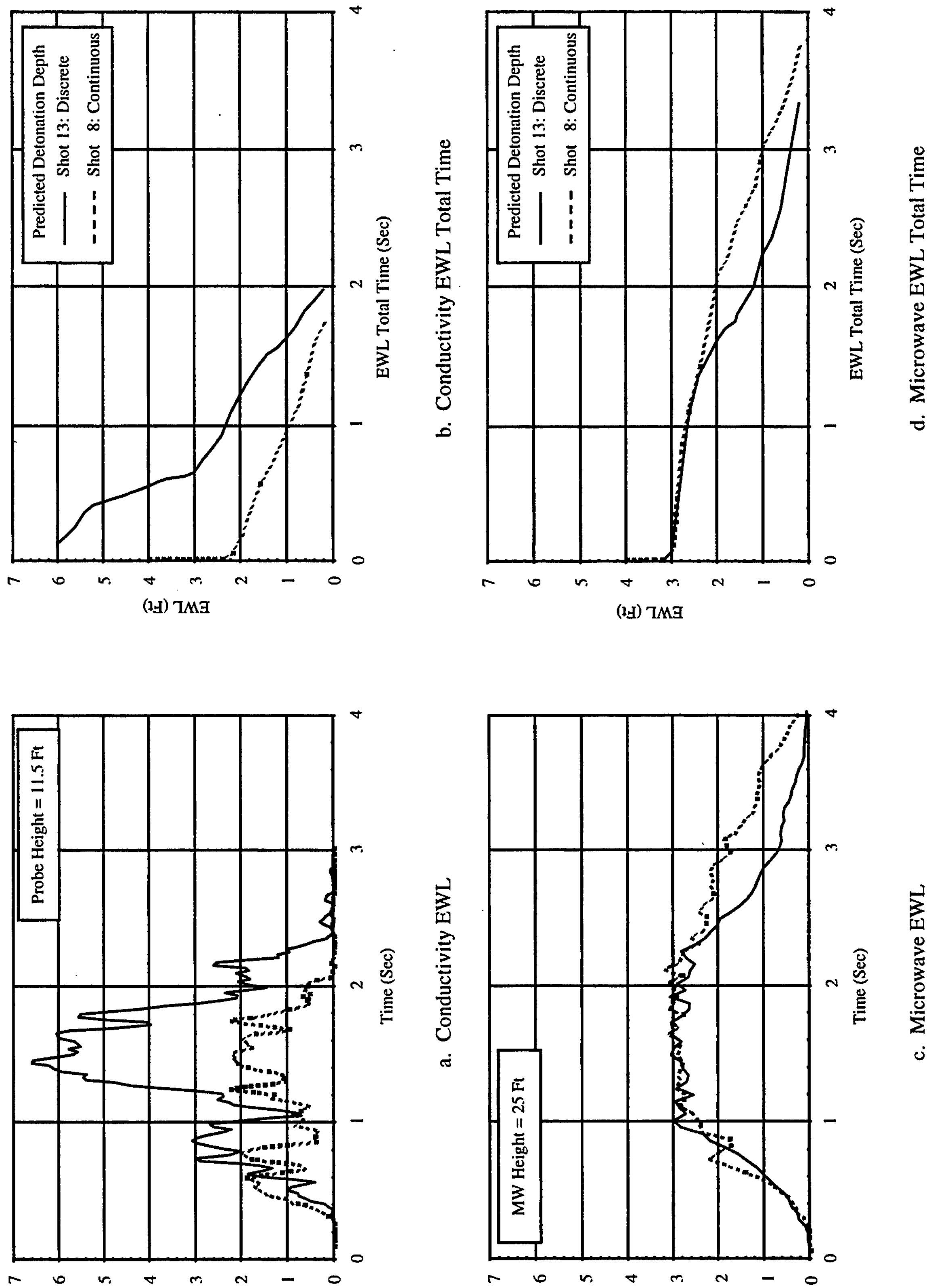
a. Conductivity EWL

b. Conductivity EWL Total Time

c. Microwave EWL

d. Microwave EWL Total Time

FIGURE 15. COMPARISON OF IDEAL AND PREDICTED CONTINUOUS LINE CHARGES



a. Conductivity EWL

b. Conductivity EWL Total Time

c. Microwave EWL

d. Microwave EWL Total Time

FIGURE 16. COMPARISON OF PREDICTED DISCRETE AND CONTINUOUS LINE CHARGES

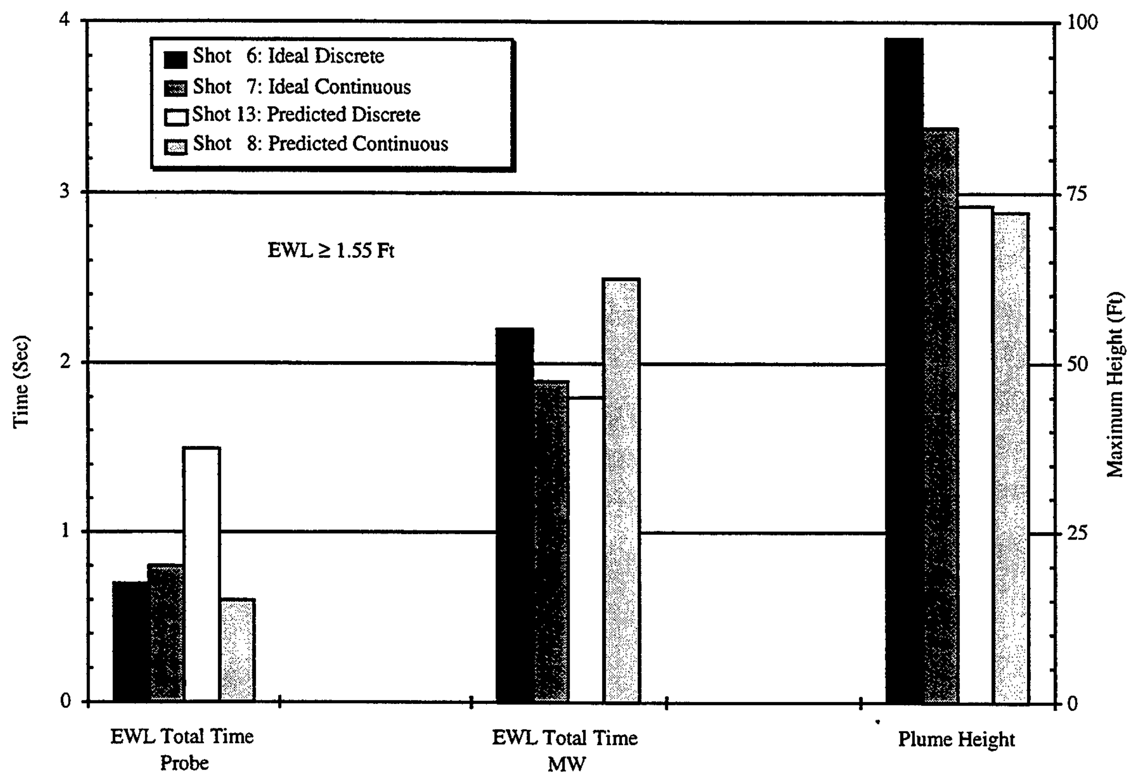


FIGURE 17. LINE CHARGE DISTRIBUTION SUMMARY

In practice, the amount of water generated from the shallow detonation of line charges may vary because of line charge configuration type, detonation depth, deployment scheme, and sea state. The results shown in Figure 17 indicate that line charge configuration differences and charge depth variations within reasonable bounds appear to have no serious deleterious effect on the quantity of water generated at cross section heights of 11 to 25 ft. The discrete line charge seems to produce slightly more water than the continuous line charge at cross section heights of 25 ft at the "ideal" detonation depth. Whereas, the continuous line charge appears to produce more water than the discrete line charge at cross section heights of 25 ft at the "predicted" detonation depth. However, neither line charge configuration offers a discernable or significant advantage of one type over the other from the standpoint of generating a water barrier. This result allows the weapon designer more latitude in designing a barrier deployment system.

DETONATION DEPTH EFFECT

Line charge detonation depth and discrete charge spacing relative to bubble diameter is the primary determinant of the amount of water ejected into the air above multiple shallow underwater explosions.[6-7] Shots 9, 10, and 12 represent discrete line charges detonated at different depths to determine the effect of the detonation depth on the amount of water in the barrier plume cross section. Shots 12, 9, and 10 were detonated at 6.8, 8.2, and 9.4 ft, respectively. Each discrete line charge consists of five C-4 explosive charges that weigh 10 lb each and are separated by 8 ft. The total line charge explosive weight is 50 lb with a total line length of 32 ft. Shots 7 and 11 represent two continuous line charges of the same linear charge density detonated at different depths. The line charge on Shot 7 was 56 ft long with a total explosive weight of 70 lb. This line charge was detonated at a depth of 8.2 ft. The Shot 11 line charge was 40 ft long with a total explosive weight of 50 lb. The detonation depth for this shot was 9.4 ft. Table 3 lists the line charge configurations and characteristics for these shots.

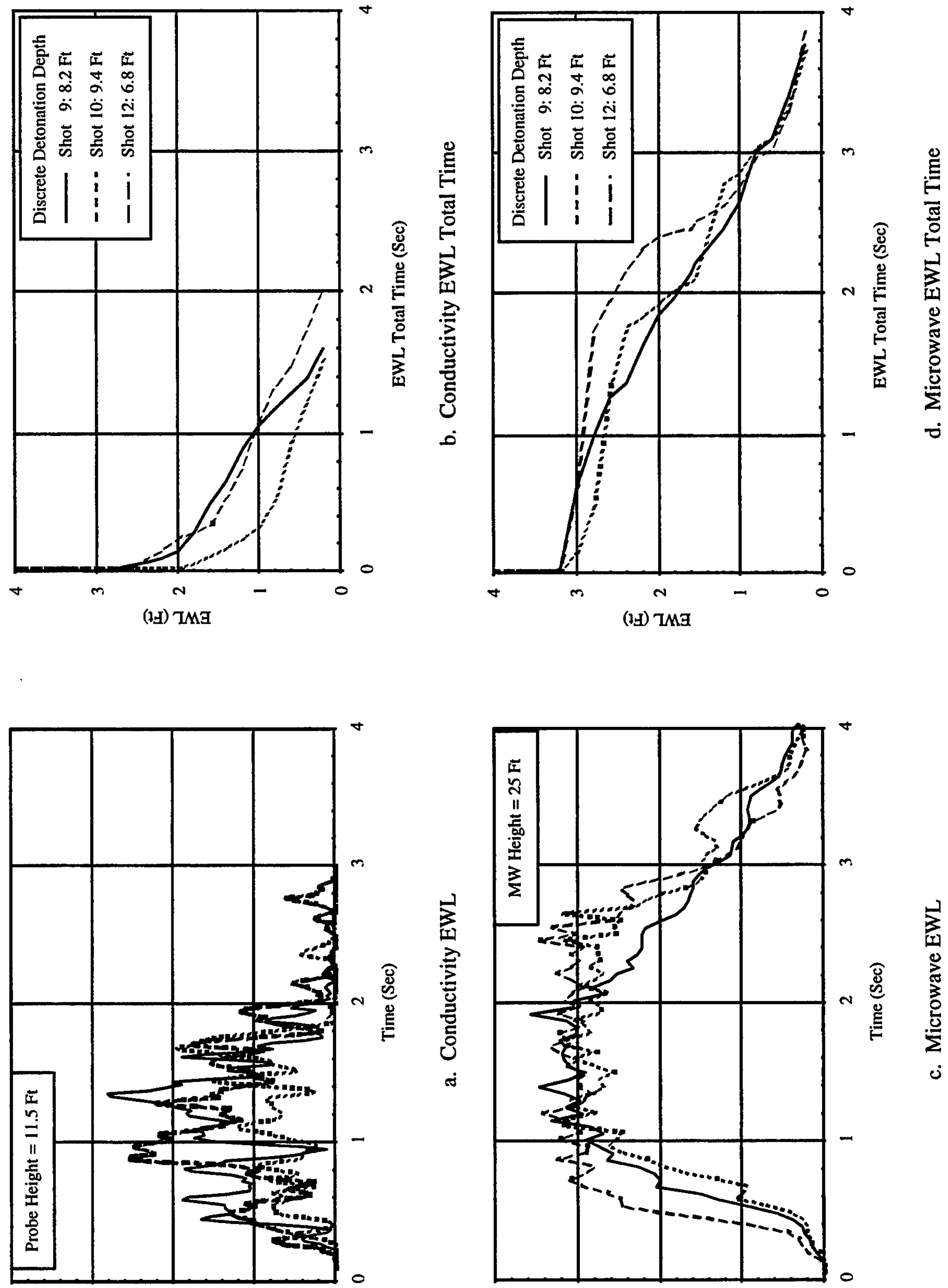
Figure 18 compares the EWL and EWL Total Time for discrete line charge plumes detonated at three different depths. The discrete line charge detonated at 8.2 ft generates a plume with a maximum conductivity EWL of 2.9 ft at 1.3 sec from detonation in Figure 18a. A detonation depth of 6.8 ft produces a plume with a maximum EWL of 2.6 ft at 0.9 sec. Finally, a detonation depth of 9.4 ft produces a plume with a maximum EWL of 2.0 ft at 1.7 sec. In Figure 18b, the EWL Total Time indicates that more water is generated at a height of 11.5 ft from the shallow detonation depths of 6.8 and 8.2 ft than at a deeper depth of 9.4 ft. Additionally, the microwave data in Figures 18c and 18d indicate that more water is generated at a height of 25 ft from the shallow detonation depth of 6.8 than at the deeper depths.

TABLE 3. DETONATION DEPTH EFFECT SHOT CHARACTERISTICS

Shot	Type	Depth (ft)	No. Of Charges	Charge Separation (ft)	Total Weight (lb)	Length (ft)	Charge Density (lb/ft)	L/D
9	Discrete	8.2	5	8	50	32.0	1.25	1.37
10	Discrete	9.4	5	8	50	32.0	1.25	1.37
12	Discrete	6.8	5	8	50	32.0	1.25	1.37
7	Continuous	8.2	(56)	---	70	56.0	1.25	2.40
11	Continuous	9.4	(40)	---	50	40.0	1.25	1.70

Figure 19 compares the EWL and EWL Total Time for continuous line charge plumes detonated at two different detonation depths. Figure 19a shows that the continuous line charge detonated at 8.2 ft generates a plume with a maximum conductivity EWL of 3.8 ft at 1.2 sec after detonation. A detonation depth of 9.4 ft produces a plume with a maximum EWL of 1.8 ft at 0.9 sec. In Figure 19b, the EWL Total Time indicates that more water is present in the plume at 11.5 ft for the continuous line charge detonated at 8.2 ft than detonated at 9.4 ft. In Figure 19c, the microwave data for the continuous line charge detonated at a depth of 8.2 ft were truncated at an EWL of 1.55 ft due to a failure in the second DLVA in the microwave receiver. Since the EWL data for this line charge plume are truncated at 1.55 ft, a comparison of the EWL Total Time at this value in Figure 19d shows the continuous line charge plume at the shallow depth with a duration of 1.9 sec as compared to 1.5 sec for the line charge detonated at a depth of 9.4 ft. A comparison of the two curves in Figure 19d seems to indicate that the continuous line charge detonated at 8.2 ft generates more water at a height of 25 ft than at a detonation depth of 9.4 ft.

The effect of line charge detonation depth on the barrier plume for continuous and discrete line charges can be compared and summarized in several ways. First, using the data of Figures 18 and 19, the maximum EWL and the resultant time to reach the maximum EWL are shown in Figure 20 as a function of line charge type, detonation depth, and barrier cross section height. In Figure 20a, the maximum EWL for the probe data indicates little difference between discrete and continuous line charges in the amount of water that is generated at a cross section height of 11.5 ft between the detonation depths of 8.2 to 9.4 ft. However, the probe data of Figure 20a suggest that the optimum detonation depth to generate the largest amount of water is 8.2 ft for the discrete line charge. Figure 20b shows the time that the maximum EWL is reached at a cross section height of 11.5 ft. The time to reach the maximum EWL for the discrete line charge plume increases slightly as the detonation depth increases. While it is very difficult to make a comparison using only two data points, the probe data suggest that a continuous line charge plume may reach its maximum EWL faster than a discrete line charge plume. The microwave data of Figures 20c and 20d suggest that the optimum detonation depth to generate the largest amount of water in the fastest time is 8.2 ft for the discrete line charge. The one data point that is available for the continuous line charge at a detonation depth of 9.4 ft matches the maximum EWL and the time to reach the maximum EWL for a discrete line charge plume at the same detonation depth.



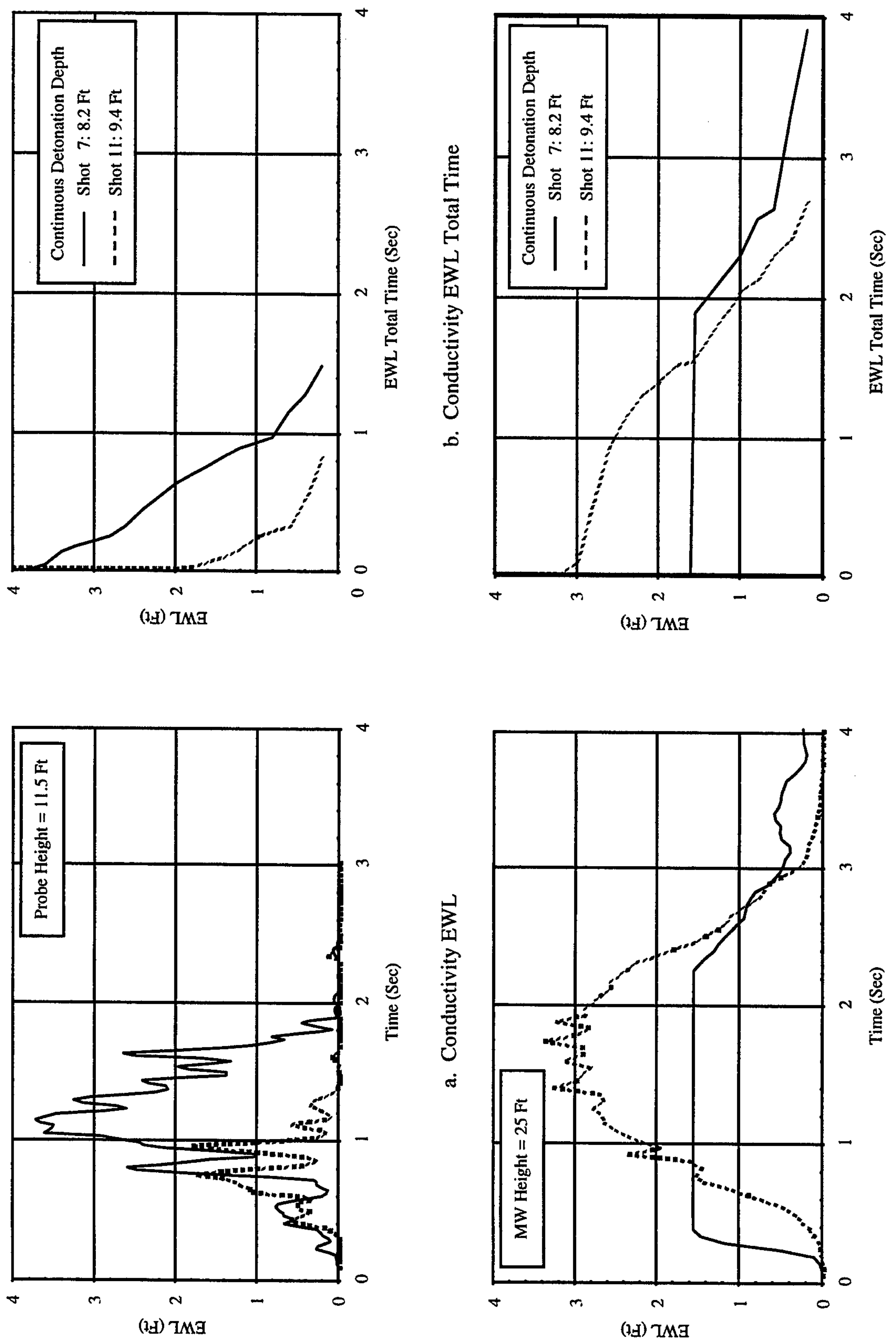
a. Conductivity EWL

b. Conductivity EWL Total Time

c. Microwave EWL

d. Microwave EWL Total Time

FIGURE 18. COMPARISON OF DETONATION DEPTHS FOR DISCRETE LINE CHARGES



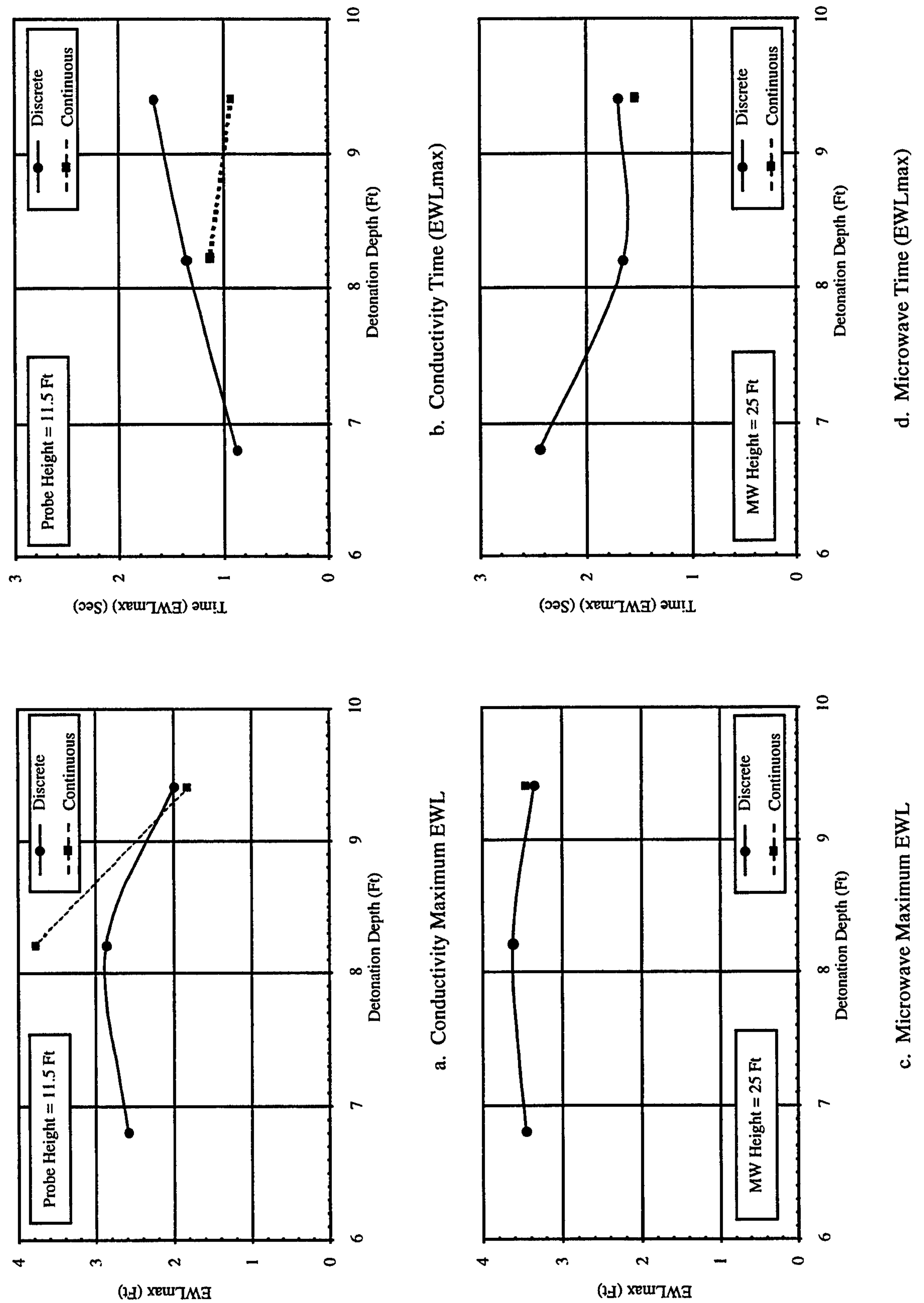
a. Conductivity EWL

b. Conductivity EWL Total Time

c. Microwave EWL

d. Microwave EWL Total Time

FIGURE 19. COMPARISON OF DETONATION DEPTHS FOR CONTINUOUS LINE CHARGES



a. Conductivity Maximum EWL

b. Conductivity Time (EWLmax)

c. Microwave Maximum EWL

d. Microwave Time (EWLmax)

FIGURE 20. DETONATION DEPTH COMPARISONS, MAXIMUM EWL

Another way to summarize and compare the effect of line charge detonation depth on the barrier plume for continuous and discrete line charges is to chose an EWL of 1.55 ft as the basis of comparison. This value of EWL is chosen since the microwave EWL for Shot 7 is truncated at 1.55 ft. Figure 21 illustrates the EWL Total Time that the EWL is ≥1.55 ft and the resultant rise time to first reach EWL = 1.55 ft as a function of detonation depth and line charge type. In Figure 21a, the EWL Total Time for the probe data indicates very little difference in the amount of water generated at a cross section height of 11.5 ft from a continuous or discrete line charge between the detonation depths of 8.2 to 9.4 ft. However, the probe data of Figures 21a and 21b suggest that the optimum detonation depth to generate the largest amount of water in the fastest time for the discrete line charge is 8.2 ft. In Figure 21c, the microwave data indicate that a discrete line charge generates slightly more water at a cross section height of 25 ft than does a continuous line charge for detonation depths between 6.8 and 9.4 ft. Figure 21d shows that the resultant rise time to reach an EWL ≥1.55 ft gradually increases as a function of increasing detonation depth for both discrete and continuous line charges.

A final comparison of the effect of line charge detonation on the barrier plume for discrete and continuous line charges uses the plume video data from the field test.[11] In Figure 22, the resultant secondary plume diameters (i.e., barrier cross section thickness) are compared to the secondary rise times to reach the barrier cross section heights of 11.5 and 25 ft as a function of detonation depth and line charge type. The video data of Figure 22a suggest that the optimum detonation depth is 8.2 ft for the discrete line charge to generate the largest secondary diameter at a height of 11.5 ft. While it is very difficult to reach a conclusion using only two data points, the video data of Figures 22a and 22c suggest that a continuous line charge plume may also have the largest secondary diameter at a detonation depth of 8.2 ft. Finally, the secondary plumes generated from the discrete line charges reach the barrier cross section heights of 11.5 and 25 ft faster than the secondary plumes from continuous line charges as a function of detonation depth, as shown in Figures 22b and 22d.

In practice, the optimal line charge detonation depths may vary because of line charge configuration type, deployment scheme, and sea state. The resultant data from Figures 18 through 22 do not suggest a clear conclusion as to the best line charge configuration type for such a complex and chaotic process as the barrier plume formation. However, the optimal detonation depth for continuous and discrete line charges appears to center around 8.2 ft. In addition, depth variations of 6.8 to 9.4 ft appear to have no serious detrimental effect on the quantity of water generated at barrier cross section heights of 11 to 25 ft.

LINE CHARGE LENGTH EFFECT

Shots 3, 6, 9, and 13 represent discrete line charges detonated at "ideal" and "predicted" detonation depths to determine the effect of line charge length on the amount of water generated in the barrier plume cross section. Table 4 lists the line charge characteristics for this series of shots. Shots 6 and 9 are line charges that consist of 8 and 5 discrete charges, respectively. Each discrete charge is detonated at a predetermined depth or an "ideal" depth of 8.2 ft. The line charge lengths for Shots 6 and 9 are 56 and 32 ft, respectively. Shots 3 and 13 are also line charges that consist of 6 and 8 discrete charges, respectively. These individual charges are

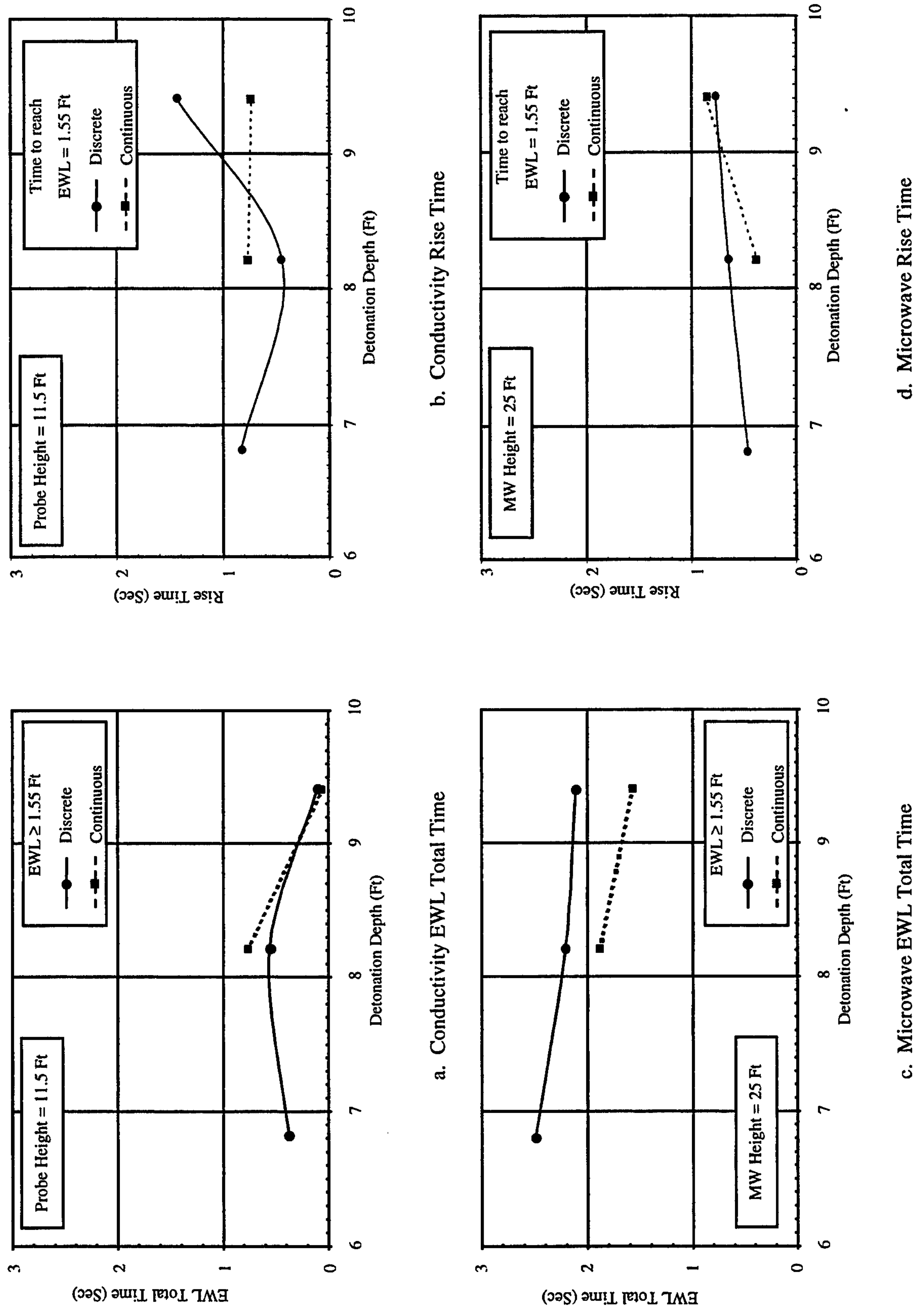
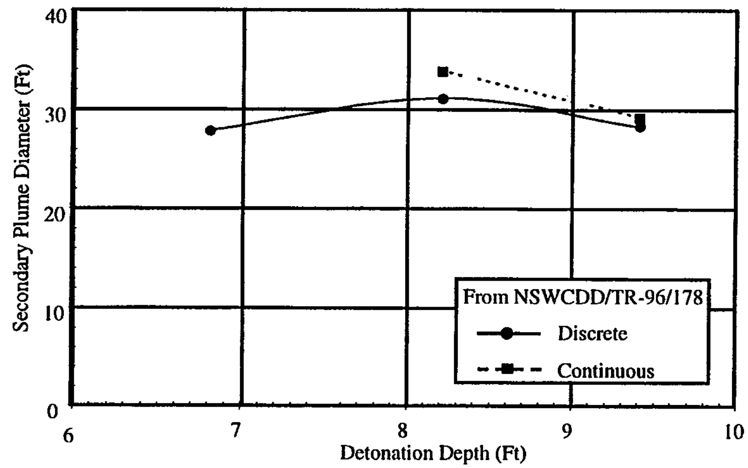
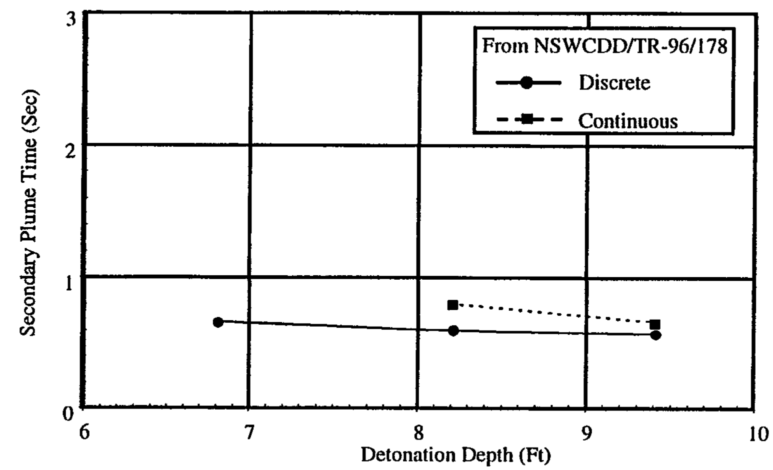


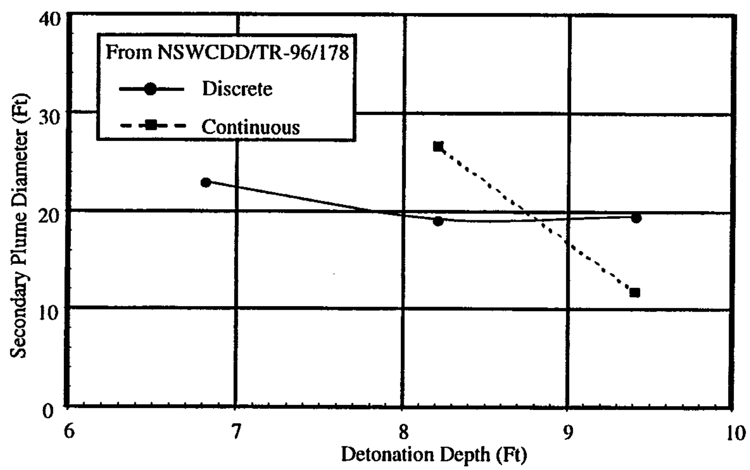
FIGURE 21. DETONATION DEPTH COMPARISONS, EWL TOTAL TIME



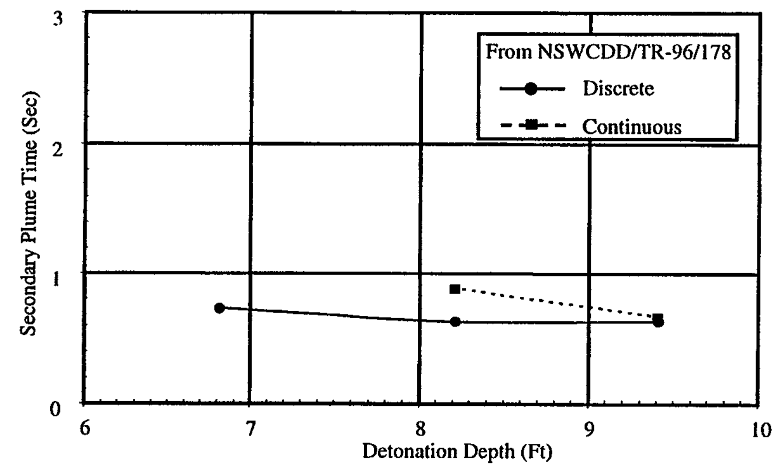
a. Secondary Plume Diameter (Hgt = 11.5 Ft)



b. Secondary Rise Time (Hgt = 11.5 Ft)



c. Secondary Plume Diameter (Hgt = 25 Ft)



d. Secondary Rise Time (Hgt = 25 Ft)

FIGURE 22. DETONATION DEPTH COMPARISONS, VIDEO DATA

TABLE 4. LINE CHARGE LENGTH EFFECT SHOT CHARACTERISTICS

Shot	Type	Depth (ft)	No. Of Charges	Charge Separation (ft)	Total Weight (lb)	Length (ft)	Charge Density (lb/ft)	L/D
6	Discrete	8.2	8	8	80	56.0	1.25	2.40
9	Discrete	8.2	5	8	50	32.0	1.25	1.37
3	Discrete	Pred	6	7 to 7.5	60	35.8	1.40	1.53
13	Discrete	Pred	8	6.75 to 7.4	80	50.3	1.39	2.10

detonated at "predicted" detonation depths as determined by a computer model of the anticipated deployment system. The detonation depths for these discrete charges vary from approximately 9 to 13 ft. The resultant line charge lengths, as projected on the water surface, are 36 and 50 ft for Shots 3 and 13, respectively.

Figure 23 compares the EWL and EWL Total Time from discrete line charge plumes of two different lengths detonated at a depth of 8.2 ft. The plume from a discrete line charge length of 56 ft (Shot 6) shows a maximum conductivity EWL of 5.6 ft at 1.6 sec from detonation in Figure 23a. A plume from a line charge length of 32 ft (Shot 9) has a maximum EWL of 2.9 ft at 1.3 sec. Even though the maximum conductivity EWL for the plume from a line length of 56 ft is approximately double the maximum EWL for the plume from a shorter line, the maximum EWL magnitudes do not provide a sense of the quantity of water within the plume over a period of time at a particular cross section height. To compare the amount of water generated from these configurations, the total time that the EWL is equal to or greater than a specific quantity (EWL Total Time) is calculated for each configuration. In Figure 23b, the conductivity EWL Total Time indicates that, at a height of 11.5 ft, slightly more water is generated for a plume generated from the longer line charge length of 56 ft than for the plume from a line charge length of 32 ft. Additionally, the microwave data in Figures 23c and 23d also indicate that slightly more water is generated at a height of 25 ft from the plume of a longer discrete line charge length than from the plume of the shorter length.

Figure 24 compares the EWL and EWL Total Time of discrete line charge plumes at two different lengths detonated at "predicted" detonation depths between approximately 9 and 13 ft. In Figure 24a, the "predicted" discrete line charge length of 50 ft (Shot 13) generates a plume with a maximum conductivity EWL of 6.6 ft at 1.4 sec from detonation. A "predicted" line charge length of 36 ft (Shot 3) produces a plume with a maximum EWL of 1.3 ft at 1.1 sec. The maximum conductivity EWL for the plume with a line length of 50 ft is approximately five times the maximum EWL for the plume with a shorter line of 36 ft. In Figure 24b, the conductivity EWL Total Time indicates that more water is generated at a height of 11.5 ft from the plume of a longer line charge length of 50 ft than from the plume of the line charge length of 36 ft. However, in Figures 24c and 24d the microwave data indicate that slightly more water is generated at a height of 25 ft from the plume of a longer "predicted" discrete line charge length than from the plume of a shorter length.

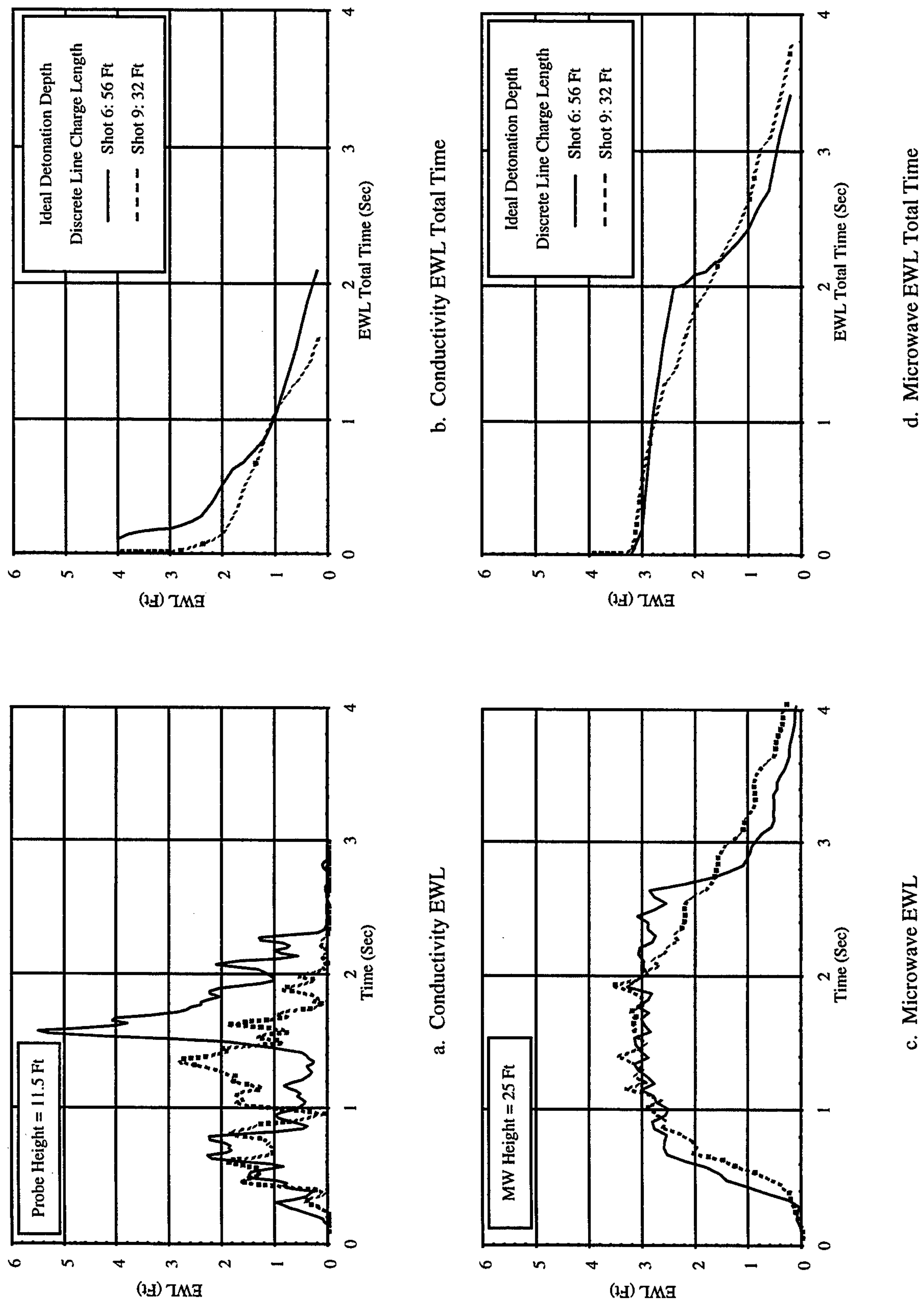


FIGURE 23. COMPARISON OF LINE CHARGE LENGTH FOR IDEAL DISCRETE LINE CHARGES

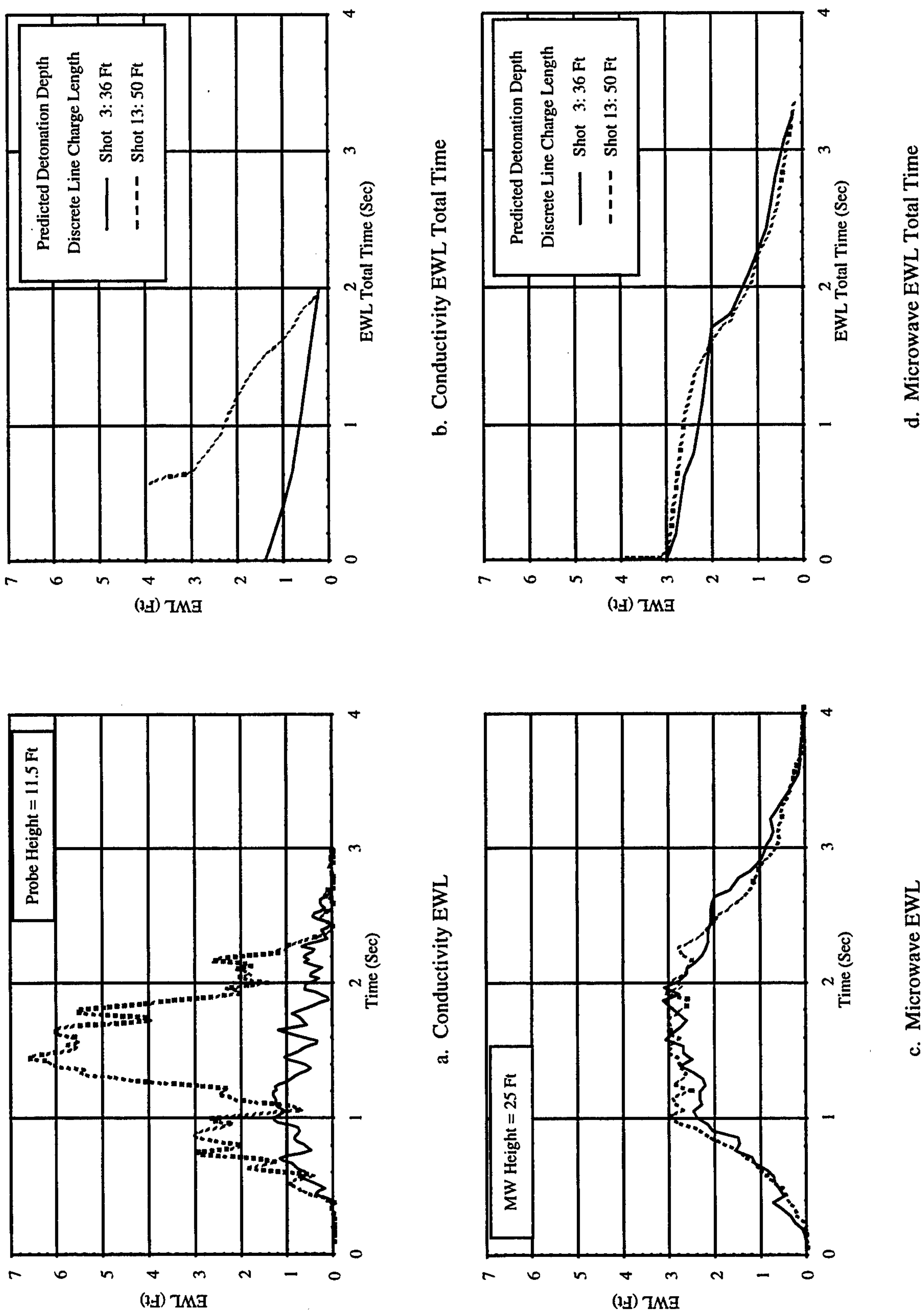


FIGURE 24. COMPARISON OF LINE CHARGE LENGTH FOR PREDICTED DISCRETE LINE CHARGES

An EWL of 1.55 ft is chosen as the basis to summarize and compare the effect of the line charge length on the barrier plume for Shots 3, 6, 9, and 13. Figure 25 illustrates the Total Time that the EWL is $\geq$1.55 ft based on the conductivity and microwave measurements for these shots. The maximum plume heights for these four line charge configurations are presented for comparative purposes.[11] From the conductivity measurements at the barrier cross section height of 11.5 ft, the duration for EWL $\geq$1.55 ft is around 0.7 sec for plumes of both line charge lengths at the "ideal" detonation depth. The line charge plume with a charge length of 50 ft (Shot 13) at the "predicted" detonation depth has the longest EWL duration of 1.5 sec at this height. The plume from the shorter line charge length of 36 ft (Shot 3) at the "predicted" detonation depth never reaches an EWL of 1.55 ft or more. From the microwave measurements at the cross section height of 25 ft, the EWL duration is approximately 2 sec for the plumes of both line charge lengths at the "ideal" detonation depth. The microwave EWL duration is approximately 1.8 sec for the plumes of both line charge lengths at the "predicted" detonation depth.

As a rule, line charge detonation lengths may vary because of line charge configuration type, deployment scheme, and sea state. The results of Figure 25 indicate that line charge length differences and charge depth variations within reasonable bounds appear to have no serious deleterious effect on the quantity of water generated at cross section heights of 11 to 25 ft. The "predicted" line charge length of 50 ft seems to produce more water than the other line charges at cross section heights of 11.5 ft. Whereas the line charges appear to produce roughly the same amount of water at cross section heights of 25 ft. A longer line charge length does not appear to generate a significantly greater amount of water than a shorter length.

PLUME REPEATABILITY

The repeatability of the line charge plume phenomena is examined by evaluating the discrete line charges of Shots 2 and 9. Table 5 lists the discrete line charge configuration characteristics for the repeatability shots. Figure 26 compares the conductivity EWL and the EWL Total Time for the discrete line charges of Shots 2 and 9. The microwave data are not included in this comparison since no microwave data were recorded for Shot 2. The line charges are fired at the "ideal" detonation depth of 8.2 ft. Figure 26a shows that the Shot 2 plume has a maximum conductivity EWL of 2 ft at 1.1 sec after line charge detonation. The Shot 9 plume has a maximum conductivity EWL of 2.9 ft at 1.3 sec after detonation. In Figure 26b, the conductivity EWL Total Time curves from the plumes of Shots 2 and 9 show close agreement in the amount of water generated. These results indicate that the plumes generated from the same line charge initial conditions appear to have a remarkable degree of repeatability.

DETONATION SEQUENCE

The detonation sequence of the line charge and its effect on the formation of the barrier plume is examined by comparing Shot 9 (sequential detonation) from this test series with Shot 3 (simultaneous detonation) from a test series conducted in the quarry at HTL in Arvonia, Virginia during the summer of 1993. The discrete charges of Shot 9 in this test series were detonated sequentially by igniting the detonating cord at one end of the line charge.

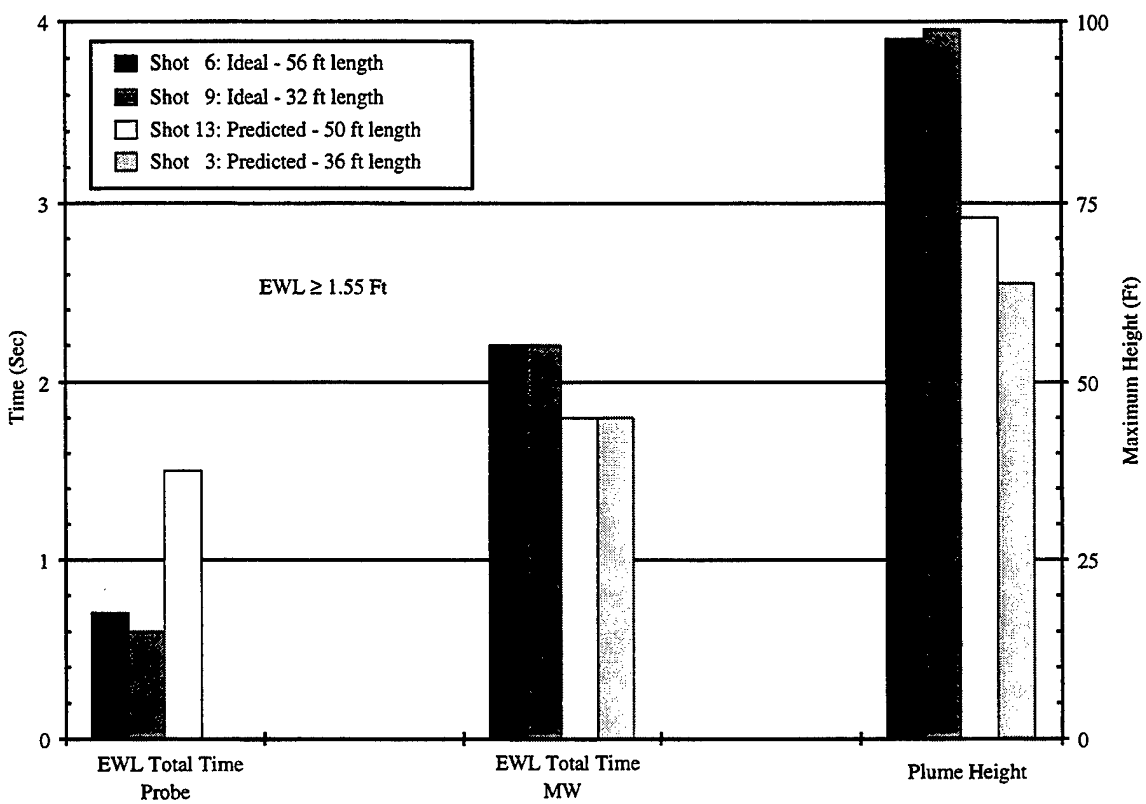


FIGURE 25. DISCRETE LINE CHARGE LENGTH SUMMARY

TABLE 5. LINE CHARGE PLUME REPEATABILITY SHOT CHARACTERISTICS

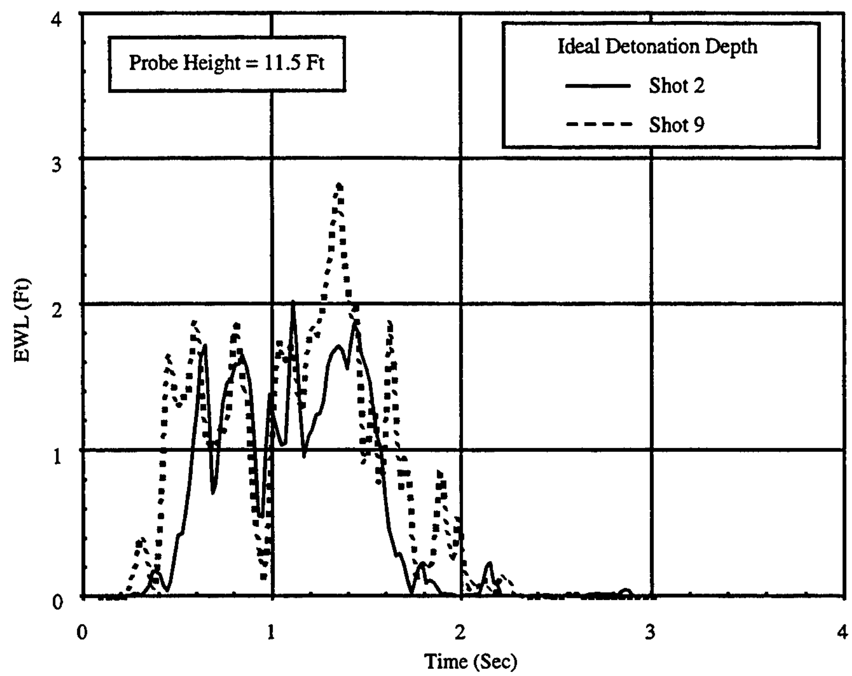
Shot	Type	Depth (ft)	No. Of Charges	Charge Separation (ft)	Total Weight (lb)	Length (ft)	Charge Density (lb/ft)	L/D
2	Discrete	8.2	5	8	50	32.0	1.25	1.37
9	Discrete	8.2	5	8	50	32.0	1.25	1.37

Each individual charge would detonate in sequence as the detonation in the cord arrived at each charge. Shot 3 in the test series fired at the HTL quarry was fired with a detonator in each charge, and all the detonators were fired simultaneously. Both shots consisted of five discrete 10-lb Composition C-4 charges that were horizontally separated by 8 ft. DTI Shot 9 of 1995 was detonated at a depth of 8.2 ft while the HTL Shot 3 was detonated at a depth of 8 ft. Table 6 lists the shot configuration and characteristics for both shots.

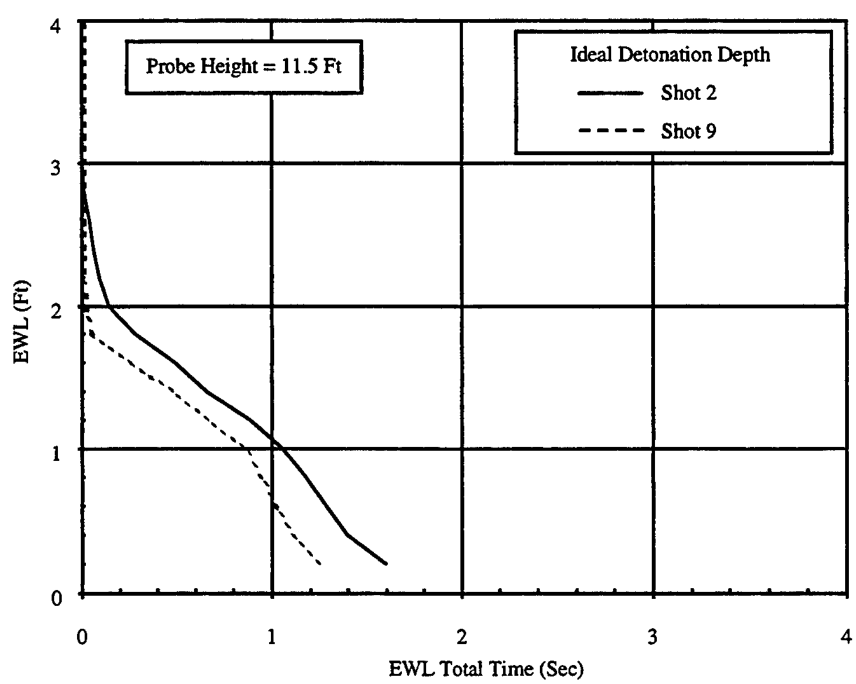
Figure 27 compares the microwave EWL and EWL Total Time for plumes from the discrete line charges of DTI Shot 9 and HTL Shot 3. The DTI Shot 9 plume reaches a maximum EWL of approximately 3.6 ft, as shown in Figure 27a. Because of the dynamic range limitations of the DLVA used in the Arvonia field tests in 1993, the HTL Shot 3 microwave measurements were truncated at an EWL of 1.55 ft. However, a comparison of the rise and fall times shows very little difference between the type of detonation sequence used to generate the barrier plume. Because of the truncated data for HTL Shot 3 at 1.55 ft, a comparison of the EWL Total Time at this value shows the plume from the sequential line charge detonation with a duration of 2.2 sec, as compared to just over 2 sec for a plume from a simultaneous detonation. While it is difficult to extrapolate a curve for the truncated microwave data, a comparison of the EWL Total Time curves appears to show very little difference between the plumes from either type of detonation sequence used to generate a barrier plume from a line charge. A comparison between sequential and simultaneous charge detonation of a line charge appears to show very little difference between the type of detonation sequence used to generate a barrier plume from a line charge.

TABLE 6. LINE CHARGE DETONATION SEQUENCE SHOT CHARACTERISTICS

Shot	Type	Depth (ft)	No. Of Charges	Charge Separation (ft)	Total Weight (lb)	Length (ft)	Charge Density (lb/ft)	L/D
DTI 9	Discrete	8.2	5	8	50	32.0	1.25	1.37
HTL 3	Discrete	8	5	8	50	32.0	1.25	1.37

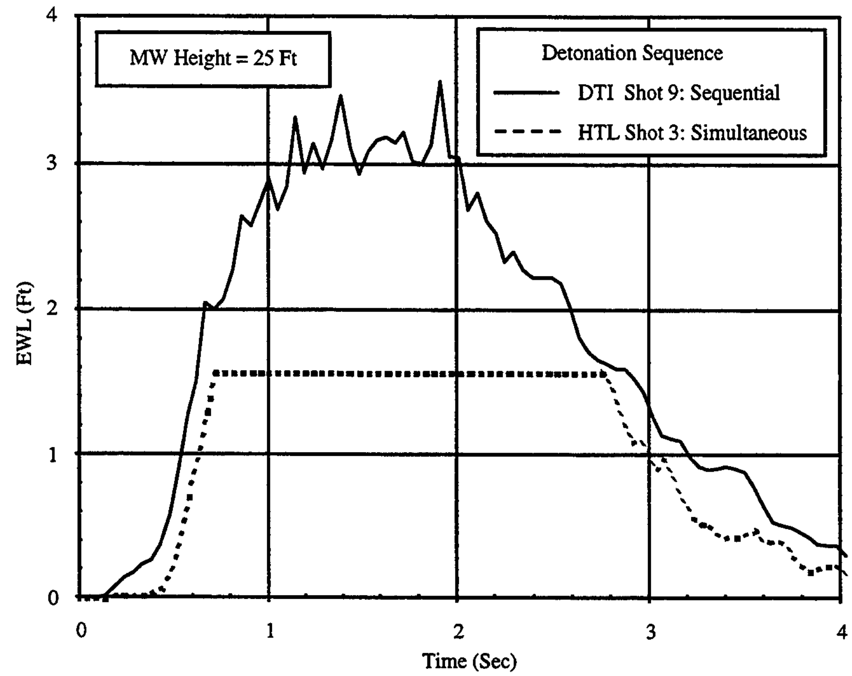


a. Conductivity EWL

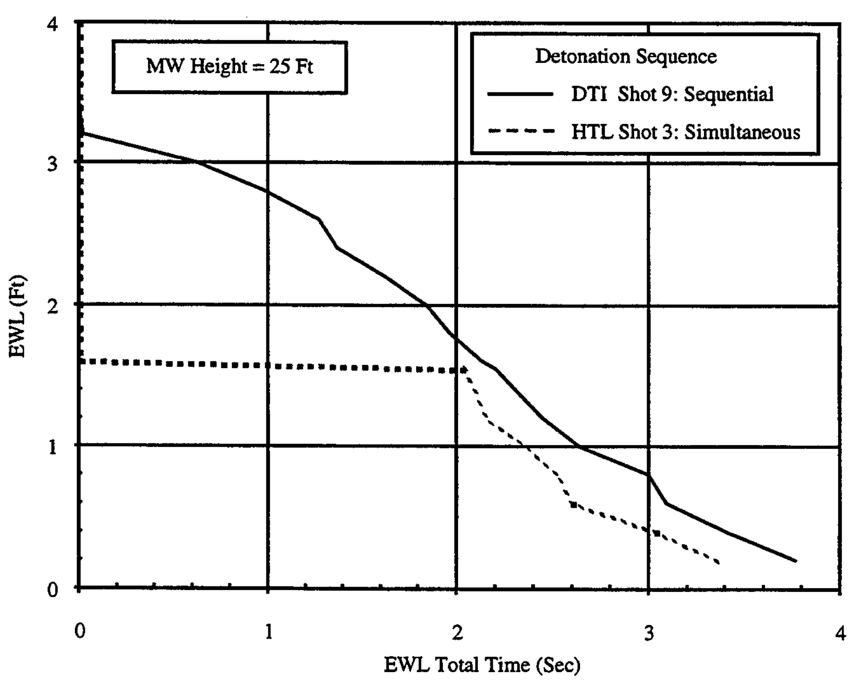


b. Conductivity EWL Total Time

FIGURE 26. COMPARISON OF PLUME REPEATABILITY FOR DISCRETE LINE CHARGES



a. Microwave EWL



b. Microwave EWL Total Time

FIGURE 27. COMPARISON OF DETONATION SEQUENCE FOR DISCRETE LINE CHARGES

SUMMARY

To support the development and evaluation of a water barrier that uses line charges, underwater detonation tests of scaled line charges were conducted during July 1995 in a 130-ft-deep, water-filled quarry operated by DTI in Rustburg, Virginia. The purpose of these tests was to evaluate a water barrier generated from the single-point detonation of simulated continuous and discrete line charges and to determine the amount and density of water ejected into the air by the subsurface detonation of these line charges. The water barrier plumes were generated by the single-point underwater detonation of Composition C-4 M113 demolition blocks that were configured into continuous line charges of 30 to 56 ft in length. Barrier plumes were also produced from the single-point underwater detonation of discrete line charges of 30 to 56 ft in length that consisted of five to eight 10-lb charges separated by 8 ft and fabricated from C-4 M113 demolition blocks. Line charge depths and horizontal separation of the discrete charges were chosen to maximize the amount of water ejected into the air.

Two measurement techniques, using microwave absorption and electrical conductivity, were employed to determine the amount and density of water in the barrier plume cross section. A microwave antenna transmitting a 4-GHz signal and a receiving antenna were placed perpendicular to the charge line at a height of 25 ft above the water surface. Fifteen conductivity probes, spaced 1 ft apart, were placed on a steel cable 11.5 ft above the water surface and in the same vertical plane as the microwave beam. The cable and probes are perpendicular to the charge line with the probes centered about the charge line. The microwave absorption and electrical conductivity measurements will be used to evaluate the water barriers generated from the single point detonation of scaled simulated line charges. In addition, the experimental measurements will be used to support the verification process of the hydrodynamic computer model that simulates the plume generation from the shallow detonation of multiple underwater explosive charges.

The experimental data for 10 shots were reduced and have been grouped to simplify the analysis of the data.

- An overall perspective of the test series is provided by the first group of shots. Four Shots (6, 7, 8, and 13) were considered together since they incorporate the effects of explosive line charge distribution and detonation depth variations for "predicted" line charges.

- The effects of varying the detonation depth were examined both for continuous line charges (Shots 7 and 11) and for discrete line charges (Shots 9, 10, and 12).

- The effects of varying line charge length were examined for "ideal" discrete line charges by Shots 6 and 9 and for "predicted" discrete line charges by Shots 3 and 13.

- Repeatability of the line charge plume phenomena were also examined for discrete charges by comparing Shots 2 and 9.

- Finally, the effect of sequential versus simultaneous detonation of discrete charges on the resultant plume was examined. This examination was conducted with a comparison of Shot 9 (sequential detonation) from this test series with Shot 3 (simultaneous detonation) from a test series conducted in the HTL quarry at Arvonia, Virginia in the summer of 1993.

In practice, the amount of water generated from the shallow detonation of line charges may vary because of type of line charge configuration, detonation depth, sea state, line charge length, and mode of detonation. Line charge configuration differences and charge depth variations within reasonable bounds appear to have no serious deleterious effect on the quantity of water generated at water barrier cross section heights of 11 to 25 ft. The discrete line charge seems to produce slightly more water than the continuous line charge at cross section heights of 25 ft at the "ideal" detonation depth. Whereas, the continuous line charge appears to produce more water than the discrete line charge at cross section heights of 25 ft at the "predicted" detonation depth. However, neither line charge configuration offers a discernable or significant advantage of one type over the other from the standpoint of generating a water barrier. The optimal detonation depth for continuous and discrete line charges appears to center around 8.2 ft. However, depth variations of 6.8 to 9.4 ft appear to have no serious detrimental effect on the quantity of water generated at barrier cross section heights of 11 to 25 ft. The "predicted" discrete line charge length of 50 ft seems to produce more water than the other discrete line charges at cross section heights of 11.5 ft. Whereas, the "ideal" discrete line charges appear to produce slightly more water at cross section heights of 25 ft. A longer line charge length does not appear to generate a significantly greater amount of water than a shorter length. A comparison between sequential and simultaneous charge detonation of a line charge appears to show very little difference between the type of detonation sequence used to generate a barrier plume from a line charge. Finally, the plumes generated from the same line charge initial conditions appear to have a remarkable degree of repeatability.

Tables 7 and 8 summarize the conductivity probe and microwave experimental data results of the plumes generated from the shallow detonation of scaled continuous and discrete line charges. The conductivity probe data, at a barrier cross section height of 11.5 ft, show that the average time for the EWL to reach 1.55 ft is approximately ¾ sec, with an average total EWL duration of around ½ sec. The slowest rise time is the "ideal" discrete line charge of Shot 10 detonated at a depth of 9.4 ft. The average maximum EWL is 3.1 ft that occurs, on average, at about 2.5 sec after charge detonation. The maximum EWL of 6.6 ft occurs in Shot 13 at 1.4 sec for a "predicted" discrete line charge.

The microwave data, at a barrier cross section height of 25 ft, show that the average time for the EWL to reach 1.55 ft is approximately ⅔ sec, with an average total EWL duration of around 2 sec. The fastest rise time is the "ideal" continuous line charge of Shot 7 detonated at a depth of 8.2 ft. The average maximum EWL is 3.4 ft that occurs on average at just under 2 sec after charge detonation.

TABLE 7. CONDUCTIVITY PROBE DATA SUMMARY (HEIGHT = 11.5 FT)

Shot	Line Charge Type	Charge Depth (ft)	Line Length (ft)	Charge Separation (ft)	Rise Time[1] (sec)	EWL Total Time[2] (sec)	EWL max[3] (ft)	Time max[4] (sec)
2	Discrete	8.2	32.0	8	0.63	0.36	2.02	1.11
3	Discrete	Pred	35.8	7 to 7.5	0.00	0.00	1.34	1.16
6	Discrete	8.2	56.0	8	0.60	0.69	5.59	1.56
7	Continuous	8.2	56.0	---	0.76	0.77	3.79	1.15
8	Continuous	Pred	53.7	---	0.50	0.59	2.33	1.24
9	Discrete	8.2	32.0	8	0.44	0.56	2.87	1.35
10	Discrete	9.4	32.0	8	1.43	0.11	2.01	1.66
11	Continuous	9.4	40.0	---	0.73	0.06	1.84	0.94
12	Discrete	6.8	32.0	8	0.84	0.37	2.58	0.87
13	Discrete	Pred	50.3	6.75 to 7.4	0.61	1.45	6.64	1.44
AVG					0.73	0.55	3.10	2.49

Notes: 1. Time to reach EWL = 1.55 ft
2. Total time that the EWL ≥ 1.55 ft
3. Maximum EWL
4. Time at maximum EWL

TABLE 8. MICROWAVE DATA SUMMARY (HEIGHT = 25 FT)

Shot	Line Charge Type	Charge Depth (ft)	Line Length (ft)	Charge Separation (ft)	Rise Time[1] (sec)	EWL Total Time[2] (sec)	EWL max[3] (ft)	Time max[4] (sec)
3	Discrete	Pred	35.8	7 to 7.5	0.89	1.82	3.13	1.87
6	Discrete	8.2	56.0	8	0.55	2.18	3.36	1.99
7	Continuous	8.2	56.0	---	0.36	1.90	1.56	0.36
8	Continuous	Pred	53.7	---	0.65	2.47	3.64	1.85
9	Discrete	8.2	32.0	8	0.65	2.21	3.62	1.65
10	Discrete	9.4	32.0	8	0.77	2.11	3.35	1.70
11	Continuous	9.4	40.0	---	0.86	1.58	3.47	1.56
12	Discrete	6.8	32.0	8	0.45	2.50	3.46	2.45
13	Discrete	Pred	50.3	6.75 to 7.4	0.77	1.80	3.34	1.94
HTL 3	Discrete	8	32.0	8	0.72	2.04	1.57	0.72
AVG					0.66	2.06	3.42	1.88

Notes: 1. Time to reach EWL = 1.55 ft
2. Total time that the EWL ≥ 1.55 ft
3. Maximum EWL
4. Time at maximum EWL

As previously stated, caution should be exercised in attempting to compare the EWL magnitudes between the microwave and conductivity measurements. Certain limitations are intrinsic to the conductivity probe design. The probe system assumes that the water droplets in the plume are comparable in size to the gap between the conductivity rods. While a significant amount of water may be present within the plume, any water droplets smaller than the rod spacing will not indicate any conductivity. Furthermore, any twist in the support line that causes the probes to point upward will cause "shadowing" of the rising plume by the probe body. Therefore, these limitations will cause the probe sets to underestimate the amount of water density that is present at the probe locations within the plume. Given these limitations for the conductivity measurements, the average EWL rise times and the average maximum EWL magnitudes show close agreement for the conductivity and microwave measurements. For both measurements, the average EWL rise times are approximately 0.7 sec and the average maximum EWL magnitudes are just over 3 ft.

CONCLUSIONS

To support the development and evaluation of the Water Barrier Concept, underwater detonation tests were conducted by NSWCDD in July 1995 to generate a water barrier from the single-point detonation of simulated continuous and discrete line charges. The simulated line charges were fabricated from scaled charges of Composition C-4 demolition blocks. Electrical conductivity and microwave absorption measurements were made on the barrier plume cross section to determine the density or quantity of water ejected in the air from the single-point detonation of the scaled line charges. The results from this series of test shots indicate that a continuous wall of water with a measured EWL on the order of 3 to 3.5 ft can be formed within 0.7 sec from the single-point detonation of simulated continuous and discrete line charges. The barrier plume shapes and quantities of water generated from these simulated line charges appeared to be consistent with the preliminary hydrodynamic model predictions. The barrier formation from the scaled simulated line charges of C-4 appear to be very robust to variation in line charge type, line charge detonation depth, line charge length, and detonation method.

Based on the video and measurement data collected from the field test, the primary conclusion of this field test indicates that water barrier formation and deployment can be built on existing, shallow water mine clearance, line charge systems, such as the M58 Linear Demolition Charge, Shallow Water Assault Breeching (SABRE) System, Distributed Explosive Technology (DET) System, and Explosive Neutralization-Advanced Technology Demonstration (EN-ATD). Furthermore, the formation of a robust barrier from variations in line charge type, detonation depth, line charge length, and detonation method permits the weapon designer greater design latitude in developing a barrier deployment system to meet terminal defense requirements for many ship classes.

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